NCHRP

NATIONAL
COOPERATIVE
HIGHWAY
RESEARCH
PROGRAM

REPORT 502

Geometric Design Consistency on High-Speed Rural Two-Lane Roadways

TRANSPORTATION RESEARCH BOARD
OF THE NATIONAL ACADEMIES

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

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Geometric Design Consistency on High-Speed Rural Two-Lane Roadways

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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

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The authors wish to acknowledge the many individuals who contributed to this research by participating in the mail-out surveys, the field data collection efforts, and the review of the developed guidelines.

FOREWORD

By B. Ray Derr
Staff Officer
Transportation Research Board

This report discusses geometric design consistency, particularly for rural roads. It presents rules on geometric design consistency suitable for use in an expert system such as the Interactive Highway Safety Design Model (IHSDM). The rules can also be used directly by a designer to evaluate roadway designs or to conduct reviews of existing roadways, improving design consistency and safety.

Consistency with drivers' expectations is a desirable property of roadway geometric designs. On non-urban, two-lane roads, drivers expect to operate their vehicles safely with relatively little mental effort. Geometric features that are atypical, have extreme dimensions, or are combined with other features in unusual ways violate these expectations; such features are termed geometric inconsistencies. Geometric inconsistencies can surprise the driver and reduce the safety of the road. Previous research has identified geometric features (e.g., horizontal and vertical alignment changes, intersections and driveways both channelized and unchannelized, lane drops, divided highway transitions, lane width reductions, shoulder width reductions and changes in composition) that may violate driver expectancy, particularly when they are located close together.

Under NCHRP Project 15-17, the Texas Transportation Institute reviewed the domestic and international literature on geometric design consistency and developed a comprehensive list of geometric design features for high-speed rural two-lane roads that can reduce geometric consistency or violate driver expectancy. They then identified the most critical roadway features or combinations of features and considered how they might affect driver performance. A data collection and analysis plan was developed to formulate relationships between key parameters of the features and driver performance.

At this stage of the project, it was decided that quantitative relationships could probably not be developed. A different course—developing rules for an expert system (particularly the IHSDM)—was chosen. The researchers identified the appropriate form and structure for an expert system to evaluate design consistency and produced the material required to support the expert system. After an expert review of these proposed rules, they were evaluated using case studies of existing roadways.

In addition to setting out the proposed expert system rules, the report discusses whether these rules could be applied to multi-lane highways and recommends text on design consistency for the AASHTO *Policy on Geometric Design of Highways and Streets.*

CONTENTS

GEOMETRIC DESIGN CONSISTENCY ON HIGH-SPEED RURAL TWO-LANE ROADWAYS

SUMMARY

The objective of the research was to develop guidelines that designers can use to improve the geometric design consistency on high-speed, non-urban, two-lane roadways. The research scope was intended to complement work done by FHWA that focused primarily on speed consistency. The inclusion of other geometric design elements (e.g., lane width reductions, lane drops, and driveways) addresses a broader range of inconsistencies.

Because "design consistency" is not defined in AASHTO design guidelines, a review of the literature was undertaken, and state DOTs and the research panel were surveyed to determine how they would define "design consistency." Based on the findings of the survey and the literature review, a recommended definition was developed: Design consistency is the conformance of a highway's geometric and operational features with driver expectancy.

A telephone survey of design engineers, consultants, law enforcement personnel, and accident reconstructionists was used to evaluate roadway features for their potential to influence design consistency. Using the findings of the survey and a review of the literature, geometric features were selected for potential inclusion in design consistency rules.

Geometric features or elements having the potential to violate driver expectancy or design consistency principles were evaluated for use in a rules-based consistency check. Several approaches have been used in evaluating geometric design consistency; among these approaches have been speed consistency, positive guidance, and driver workload. Based on these approaches and the principles of design consistency reviewed in the literature, the basic structure of the consistency rules was established. The structure was developed to include a brief background section on the issue, necessary models or algorithms, warning levels, and text warnings (including potential remedial measures) for the designers.

Based on the structure developed, design consistency rules were developed to notify designers and engineers when the potential for driver expectancy violations is present. Following initial development, the design consistency rules were reviewed by the research staff in a series of meetings, reviewed by the research panel, evaluated in three case studies, and revised to their final recommended form.

CHAPTER **1**

INTRODUCTION AND RESEARCH APPROACH

The goal of transportation is generally stated as the safe and efficient movement of people and goods (*1*). To achieve this goal, designers seek to provide the safest and most efficient designs that may practically be provided. The designer uses many tools and techniques to analyze and develop these designs, incorporating new information as it becomes available. One technique used to improve safety on roadways is to examine the consistency of the design. Designers are concerned with and attempt to provide consistent designs because these designs conform to the expectancies of the driver and tend to operate with fewer failures and conflicts (*2*). To develop a consistent design, however, the designer must have a good working knowledge of those expectancies.

Expectancy, in general, can be stated to represent a set of possible probabilities regarding a given situation (*3*). Those probabilities are subjective and are based upon learned and experienced events. Expectancy is a known determinant of reaction time, signal detection, and vigilance. Because the driving task involves all of these factors, attention must be placed on the driver's expectancies. An operational definition of expectancy with regard to transportation has been given by Ellis (*4*):

> Driver expectancy relates to the observable, measurable features of the driving environment which:
>
> (1) Increase a driver's readiness to perform a driving task in a particular manner, and
>
> (2) Cause the driver to <u>continue</u> in the task until it is completed or interrupted.

A similar definition was provided by Alexander and Lunenfeld (*2*):

> Expectancy relates to a driver's readiness to respond to situations, events, and information in predictable and successful ways.

Several major research efforts have attempted to learn about (and to provide information to designers about) design consistency and driver expectancy. The information has taken several forms—mainly, consistency checklists, speed consistency, and driver workload. These are summarized as follows:

- Consistency checklists may be based on subjective judgment, on empirically derived measures, or some combination of the two. These checklists are generally structured to call designers' attention to aspects of the design that affect consistency in such a manner as to meet other criteria yet still present a potential safety risk.
- Speed consistency measures have generally been constructed from empirically based measures; the intent generally is to achieve one or more of the following goals: promote uniform vehicular speeds along the roadway, reduce speed variability, or provide the means to an iterative process to enable designers to more closely match predicted operating speeds and design speeds.
- Driver workload measures are intended to "manage" the workload on the driver so that a more consistent level of effort is required on the part of the driver. Extreme features, unusual features, or combinations of features are examined for their influence on driver workload.

Rural two-lane highways have the greatest proportion of crashes on the U.S. highway system. These crashes are frequently attributed to either driver error or inadequate design. Unfortunately, the definition of inadequate design is not clear because a combination of factors can all be detrimental to a roadway design that meets or exceeds design standards. Although designers attempt to address these issues, there has been concern that designers are not doing enough to address them. Additionally, increased speeds on roadways have reduced the amount of reaction time available to drivers, further increasing the potential for driver error.

The development of consistent design practices has been a goal since at least the 1930s. Barnett developed the concept of design speed to ensure consistency (*5*). The design speed concept has undergone several modifications in recent years, but the underlying theory still exists—roadway alignments should meet or exceed the criteria for a given design speed. Although sound in theory, problems have developed with the design speed concept in its current form. Design requires alignment features to be developed individually. Difficulties arise when designers do not consider the roadway as a single element consisting of several parts—the driver, geometry, and environment. Conceptually, a breakdown in any one of these parts results in a location with a high potential for crashes. Designers cannot control two of these elements, but may account for them through the geometry. A relationship exists between traffic safety and geometric design consistency, and alignment consistency represents a key issue in modern highway geometric design. A consistent alignment will allow most drivers to operate safely at their desired speed along the entire alignment.

Existing design speed-based alignment policies in AASHTO's *A Policy on Geometric Design of Highways and Streets* (referred to as the Green Book) encourage the selection of design speeds that are ". . . consistent with the speeds that drivers are likely to expect on a given highway facility" and that "fit the travel desires and habits of nearly all drivers expected to use a particular facility" (*6*).

Researchers in the United States and other countries have focused on developing methods to account for problems associated with design consistency. The principal focus in most of these studies has been on developing measures or techniques to identify locations that may pose expectancy problems for the driver. The measures most commonly used have focused on driver expectancy, speed prediction, or driver workload.

RESEARCH OBJECTIVES AND SCOPE

The objective of the research was to develop guidelines that designers can use to improve the geometric design consistency of roadway features on high-speed, non-urban, two-lane roads. The guidelines are suitable for identifying specific problem locations and for analyzing alternative designs for new locations and for reconstruction projects.

The scope of the proposed research was carefully defined in relation to the effort conducted by the same research team in the FHWA study, *Design Consistency Evaluation Module for the Interactive Highway Safety Design Model (IHSDM)*. The FHWA study focused on geometric design consistency issues related to horizontal and vertical alignment. The product of that effort was a design consistency evaluation procedure that could be implemented as part of the IHSDM, a computer tool being developed for use by designers in conjunction with commercial computer-aided design (CAD) systems (*7*). The IHSDM allows designers to identify design inconsistencies and to change the design so as to eliminate or minimize those inconsistencies and then to apply the design consistency procedures again to verify the improvement.

The work in NCHRP Project 15-17 differs from the FHWA project in two key ways. First, the scope of the NCHRP project is more inclusive and has addressed a broader range of potential inconsistencies. In addition to horizontal and vertical alignment issues, the NCHRP research addresses other geometric features, such as intersections and driveways, lane drops (i.e., climbing or passing lane terminations), lane width reductions, shoulder width reductions, and changes in shoulder type and material. Despite the focus on these new factors, the findings of the FHWA work concerning horizontal and vertical alignment have been incorporated in the NCHRP results, and the research team has been alert for interactions between horizontal and vertical alignment and the new factors being considered.

The second key difference between the current FHWA project and the NCHRP work is that the results are presented in the form of published guidelines rather than in the form of a computer program. Although the computerized IHSDM design consistency module will be a powerful and, it is to be hoped, widely used tool, it is also important for geometric design consistency guidelines to reach engineers who are not working in a CAD environment. Published guidelines provide a tool for the following uses: application in the field or where no computer is available, diagnosis of existing sites and for application to small projects not performed in the CAD environment, application by CAD users who do not have access to the IHSDM, and training of all types of engineers in the principles of design consistency. The published guidelines can also provide a basis for implementing consistency guidelines in the design policies of individual highway agencies and in the AASHTO Green Book.

RESEARCH APPROACH

The general approach to this research was to investigate design consistency with respect to the design of high-speed, rural, two-lane roadways. The research included the following activities:

- Conduct of a critical review of the literature concerning design consistency and driver expectancy. The effort focused on identifying and reviewing literature related to factors other than horizontal and vertical alignment and on identifying resources, including research results and databases from other recently completed or ongoing studies.
- Development of a comprehensive list of geometric design features that influence design consistency, identification of the most critical features and/or combinations of features that affect driver performance, and identification of those aspects of those features that may lead to inconsistencies. In addition to review of the literature, a survey of design engineers, consultants, law enforcement personnel, and accident reconstructionists was undertaken to develop and refine the list of influences on design consistency.
- Development of measures of effectiveness that can be used to assess the design consistency of various roadway geometric elements.
- Development of an acceptable definition for the term "design consistency." A survey of state DOTs was conducted to ascertain reactions to definitions found in the literature and developed by researchers. Alternative definitions were also sought in the survey.
- Development of guidelines for use in evaluating design consistency on high-speed, non-urban, two-lane roadways. The guidelines address various design consistency

problems and present background material to support the conclusions and recommendations. The guidelines also provide examples of design consistency problems, critical causal factors, and recommended countermeasures that have proven effective.

- Preparation of the guidelines so as to support the development of an expert system capable of reviewing designs for consistency.
- Conduct of pilot tests using the completed guidelines.
- Evaluation of the guidelines for their applicability to high-speed multilane facilities, with partial or no control of access.

ORGANIZATION OF THIS REPORT

The remainder of this report consists of three chapters and five appendixes. Chapter 2 summarizes the findings of the study. Chapter 3 provides the form and structure of the rules system developed and the design consistency rules. Chapter 4 summarizes the conclusions of the study and provides suggested changes for the AASHTO Green Book (*6*).

The appendixes elaborate on the literature review, geometric design features that influence design consistency, the survey on definitions, the case studies, and the recommended changes to the AASHTO Green Book.

CHAPTER 2

FINDINGS

Several efforts were undertaken to review design consistency and its application to two-lane rural roadways. A review of the literature, a survey on geometric features that could influence design consistency, and a survey on the definition of "design consistency" were conducted.

Design consistency is a tool or measure used to evaluate or modify roadway designs for consistency with driver expectancy. Features should be considered from the viewpoint that they affect driver decision-making or ability. Inclusion of particular geometric features in a design consistency methodology is contingent on at least two issues:

- Does a feature affect driver response or behavior?
- Does a change in that feature result in a change in driver response or behavior?

LITERATURE REVIEW

A review of the literature related to design consistency was undertaken. The literature review is presented in Appendix A, although specific findings are included elsewhere in this chapter where appropriate.

SURVEY ON GEOMETRIC DESIGN FEATURES

A survey was undertaken to review geometric design features that could influence design consistency. Design engineers, consultants, law enforcement personnel, and accident reconstructionists (17 in total) were contacted and surveyed via telephone. The survey provided the respondents' views on the geometric features most critical for design consistency purposes.

A list of roadway features (e.g., vertical curve and pavement cross-slope) or feature aspects (e.g., radius of horizontal curve and intersection skew angle) was developed for the survey. The features were rated on a scale of 1 to 10 (1 as least influential and 10 as most influential); a score of 0 was assigned when respondents did not believe the feature had an influence on design consistency. The features' average scores are provided in Table 1.

The features had an overall average rating of 3.7, although a relatively clear demarcation was present between features commonly indicated to have a high influence on design consistency and those thought to have a low influence on design consistency. Several rating schemes were evaluated. The research team was concerned that individuals rating a feature at 10 could unduly influence the combined rating scores and that "mediocre" elements that received middle scores from most respondents also could have an undue influence. As a compromise, a ratings scheme based on whether a feature had an average rating of 5 or more and received multiple ratings of 10 resulted in the following features being selected for further evaluation:

- Driveways (access points);
- Sight distance, i.e.,
  - Along the roadway and
  - At an intersection;
- Superelevation;
- Passing lanes at an intersection;
- Combined features, i.e.,
  - Horizontal and vertical curves,
  - Vertical curve and intersection, and
  - Vertical curve, horizontal curve, and intersection; and
- Traffic control devices, i.e.,
  - Lane markings (e.g., paint and buttons),
  - Passing/no passing markings,
  - Lane marking transitions.

Other features with above average ratings and multiple ratings of 9 or above included the following:

- Intersection presence in general;
- Shoulder presence in general;
- Obstructions along the road, i.e.,
  - Visual obstruction and
  - Impact problem; and
- Combined feature: horizontal curve and an intersection.

SELECTION OF ELEMENTS FOR FURTHER STUDY

One approach to the development of a list of features that warrant further study would be to focus on those elements that appear to influence successfully used consistency measures of effectiveness (MOEs) yet have not had their influence on those MOEs fully analyzed. Based on that criterion,

TABLE 1 Elements in telephone survey

General Elements		*Passing Lanes*	
6.1	Driveways (access points)	4.2	Presence
4.8	Topography (mountainous/rolling/plains)	2.9	Transitions
1.4	Tangent length (length of straight section)	3.9	Length
1.6	Cross-slope (slope across the roadway)	4.9	Presence at intersection
Sight Distance		*Shoulder*	
5.8	Inadequate vs. adequate	3.9	Presence
3.5	Along a roadway	3.2	Type (paved/gravel/grass)
5.9	At an intersection	3.4	Width
Intersections		*Obstructions along the Road*	
4.4	Presence in general	4.2	Presence in general
4.5	Skew angle (crossing angle)	5.5	Visual obstruction
2.4	Channelization	3.4	Impact problem
2.9	Lighting	2.4	Continuous (berms, barriers, etc.)
2.7	Speed change lanes (deceleration/acceleration lanes)	3.2	Intermittent (trees, rocks, shrubs, etc.)
3.9	Spacing between intersections	*Drainage Structures*	
3.1	Left turn lane offset	2.4	Ditch or channel along the roadway
2.8	Left turn lane length	2.6	Ditch or channel crossing the roadway
Median		1.9	Ditch shape
1.9	Presence in general	*Combined Features*	
2.0	Type	5.4	Horizontal and vertical curves
1.9	Width	5.6	Horizontal curve and an intersection
2.1	Transition from no median to median	6.5	Vertical curve and an intersection
2.4	Transition from median to no median	7.1	Vertical and horizontal curve and an intersection
Vertical Curve		*Traffic Control Devices*	
2.4	Presence in general	4.2	Lane markings (paint, buttons, etc.)
1.9	Sag	4.9	Passing/no passing markings
4.2	Crest	3.2	Lane marking transitions
4.4	Sharpness	3.8	Intersection delineation
2.4	Length	3.1	Lane assignment signs (allowed use) at intersections
Horizontal Curve			
4.1	Presence in general	2.0	Advisory speed limit signs
5.0	Radius	3.2	Regulatory speed limit signs
3.5	Deflection angle (bend)	2.8	Guide signs (destination/route signs)
3.0	Length		
4.8	Superelevation (banking)		
5.5	Vision through curve		

it would appear that horizontal and vertical curves could be selected for further study based on their demonstrated influence on speed (*7*).

In Fitzpatrick et al.'s study (*7*), the development of recommended equations for various combinations of horizontal and vertical curves was used to develop regression equations to predict 85th percentile speed on roadway segments. The results from 22 sites that included limited sight distance vertical curves and horizontal curves were used to develop regression equations for predicting speed. The only significant variable found was radius, however.

Additional input to the selection of geometric elements from currently used consistency measures in the literature and practice would emphasize those elements that influence speed. Other geometric elements found to influence speed include lane and shoulder width. Further studies examining their influence on speed could be productive in adding to current knowledge regarding speed consistency. Sight distance could be a measured characteristic in some of the studies, as appropriate. Based on previous work, horizontal curve radius is a focal point. It received a relatively high average rating (5.1), with 1 rating of 10 and 3 ratings of 8.

SURVEY ON DESIGN CONSISTENCY DEFINITION

Developing a recommendation for the definition of design consistency was considered necessary because there was no widely acknowledged definition in the field of transportation. Surveys were distributed to the U.S. state DOTs and transportation researchers. Of the 99 surveys sent, 53 were returned, for a return rate of 54%. Surveys were returned from 32 state DOTs.

The survey asked the following question about the definition of design consistency: "Which of the following definitions is the closest to your preferred definition?" Five prepared definitions were provided; space was also provided for alternative definitions and comments. Table 2 summarizes the responses and lists the number of respondents preferring a particular definition, as well as a review of common phrases and ideas included in the alternative definitions.

Many of the alternative definitions did not vary greatly from those included in the survey, frequently using phrases combined from two of the provided definitions. The most common factors in the alternatives were "avoidance of abrupt change" and referring to similar highways or sections of highways.

Preference for a definition referring specifically to speed uniformity was relatively low and was expressed by only three respondents. Of those three, two referred to operating speed and one to design speed. One respondent preferred the definition that referred to limiting driver workload.

The inclusion of reference to a "similar roadway" or "section of highway" is attractive, but the intent of that phrase appears to be embedded within the phrase "driver expectancy." Driver expectancies are based on their experiences in the immediate past and over their driving careers. Definitions that include terms regarding highway "sections" are problematic for that reason; achieving an acceptable definition of a "section" appears unlikely as well. Driver expectancy is adaptive, with modifications of that expectancy based on facility type and region. "Abrupt change" is another phrase that would appear to be potentially useful, but its inclusion would not appear to add substantially to the recommended definition. Reference to a specific measure of effectiveness would appear to be unreasonably limiting and is thus not preferred, although it could simplify any proposed system.

The recommended definition for design consistency is as follows:

Design consistency is the conformance of a highway's geometric and operational features with driver expectancy.

This definition can be applied to a wide range of conditions (i.e., horizontal alignment as well as intersections) because it is not limited to a single measure or type of measure and was preferred by the largest number of respondents. Acceptance was by no means universal, but this definition appeared to be the most applicable with regard to using multiple measures of effectiveness and various situations.

METHOD USED TO DEVELOP RULES

Following completion of the consistency survey and review of the literature, a series of meetings was held to develop and then review the design consistency rules. The interaction between researchers was used to develop and refine insight into design consistency and the issues under review.

In the first meeting, the research team reviewed the results of the design consistency element survey and the literature review. The form and structure of the consistency check system were developed, setting preliminary criteria for inclusion in the consistency rules system, measures of consistency, and the nature of warning messages to be provided. The research team also developed a preliminary list of elements to be examined for their consistency. Priorities were also set for the individual elements, providing a measure of the research team's view of the potential for the impact of the elements on design consistency measures. The individual elements

TABLE 2 Summary of survey responses

Number of Respondents	Definition
19	...the conformance of a highway's geometric and operational features with driver expectancy.
4	...the avoidance of abrupt changes in geometric features for continuous highway elements and the more careful use of design elements to meet driver expectancies.
4	...the agreement of the geometric and operational aspects of the roadway with driver expectancy.
3	...the similarity in appearance and function of roadway features to previous features encountered by the driver.
3	...the lack of abrupt changes in geometric features that might affect driver behavior for contiguous highway elements and design elements in combination.
19	These respondents provided alternative definitions. Most used terms or phrases from the definitions provided, with some additional material or combination of definitions. Of those 19: • 5 used the phrase "avoidance of abrupt changes" in relation to operations, meeting expectancy, or adversely affecting driver behavior • 6 referred to a "given section of roadway," "given environment," "similar roadways," or other wording • 3 included the phrase "similarity in appearance" of roadway features • 3 respondents joined together in recommending "An arrangement of highway features that minimize the potential for adverse driver reactions due to surprise or misinterpretation" • 3 respondents joined together in recommending "The avoidance of abrupt changes in geometric and operational features for continuous highway design elements and the careful selection of design elements that meet driver expectancies" • 2 referred to speed, referring to "consistent with an appropriate design speed" and "such that uniform operating speeds are observed"

were then assigned to the members of the research team for further investigation.

Following research panel review of the consistency rules form and structure and a preliminary list of included elements, researchers developed preliminary rules for review by the project team. Following a review period, the research team held a second meeting to present and discuss the consistency rules. Several were substantially modified or eliminated on the basis of the findings of the researcher presentations.

A third meeting was held to finalize the preliminary rules, with further discussion and review of the basis and nature of the rules. Next, the rules were submitted for panel review and comment. The rules consist of the following:

- Background section regarding the nature of the inconsistency;
- Models or tables needed to evaluate the inconsistency;
- Warning levels, i.e.,
  - Level 2 warning—lower severity and
  - Level 1 warning—higher severity; and
- Potential remedial treatments.

The case studies, presented in Appendix D and summarized below, also provided an opportunity for review and modification of the rules.

CASE STUDY RESULTS

Following the development of draft design consistency rules, three case studies were completed. The sites were selected to meet the following criteria:

- Rolling terrain,
- Moderate traffic volumes,
- Rural conditions, and
- High-speed traffic.

State DOT personnel in two states (i.e., Oklahoma and Texas) were contacted to obtain information regarding candidate sites. Test sections 5–7 km [3–4.5 mi] were selected for evaluation. The research team examined the roadways by

- Reviewing construction plans;
- Videotaping the roadway segment;
- Locating driveways; and
- Measuring speeds of 100 free-flow vehicles using laser guns on relatively flat, straight sections of the highways.

Each of the roadways triggered Level 2 warnings related to driveway spacing and offsets, indicating moderate inconsistencies. The rules were later modified to eliminate (1) field entrances (infrequently used entrances to agricultural areas) and (2) driveways at residences from the criteria established for the rule, because of the unlikelihood of vehicles arriving at similar times at these types of infrequently used driveways. Using the modified criteria, the warnings would not have been triggered.

Each of the roadways triggered Level 2 warnings related to the lack of passing opportunities. Substantial platoons were apparent on the roadways, although a formal study of the roadways' passing operations was not undertaken. The roadway examined in Case B is under consideration for the installation of passing lanes in improvements planned for the near future.

Test Case A had one location that met the Level 2 warning criteria for frequency of decisions on roadway segments. Four of the critical features were present within 450 m [1,500 ft].

Based on the use of the design consistency rules in the case studies, two modifications were made to the rules. The driveway separation and offset rules were modified to apply to commercial and high-volume driveways. In response to panel comments, the rule related to tight horizontal curves with wide shoulders was modified to refer to shoulder widening greater than current AASHTO recommendations that provide such widening under certain circumstances of pavement width and traffic volume.

CHAPTER 3

INTERPRETATION, APPRAISAL, AND APPLICATIONS

The research team developed the form and structure for a proposed expert system on design consistency. Based on work previously reported in the literature, a framework was established to aid in the development of design consistency rules.

EXPERT SYSTEM FORM AND STRUCTURE

The research team developed the basis for an expert system on design consistency to supplement work done by others in the development of FHWA's Interactive Highway Safety Design Model (IHSDM). In order to place the proposed design consistency system into perspective, a brief review of previously developed work on design consistency is presented.

The development of an expert system that expands the boundary of what is examined with regard to design consistency is dependent on the definition of "design consistency" and the comprehensiveness of the system. Research projects in the past have sought to develop programs that review design consistency either quantitatively (i.e., Messer, Mounce, and Brackett's *Methodology for Evaluating Geometric Design Consistency* (*8*) or Fitzpatrick et al.'s *Alternative Design Consistency Rating Methods for Two-Lane Rural Highways* (*9*)) or qualitatively (i.e., Alexander and Lunenfeld's work on design consistency (*2*)), with varying degrees of success.

Because the search for an easily defined and examined measure of effectiveness leads to a quantitatively based procedure, an approach similar to the procedures of Messer, Mounce and Bracket or Fitzpatrick et al. was preferred. Each of these design consistency procedures is based on readily measurable factors, and, in both cases, a single measure is produced to allow the evaluation of the consistency of a roadway. Alexander and Lunenfeld's approach differs from those procedures, focusing on a more qualitative review of expectancy violations and driver information needs. Each of these procedures has associated strengths and weaknesses, which will be reviewed briefly.

Messer, Mounce, and Brackett

This procedure, developed for two-lane rural highways, attempts to rate individual features of the highway through the use of laboratory and empirically developed curves and tables, then modify those ratings by the use of factors based on sight distance, driver unfamiliarity, feature expectancy, carryover, and 85th percentile speed. The method has been successfully validated in at least two instances (*10, 11*), although concern has been raised over its applicability to roadways with complex alignments. Because the rating for each feature is dependent on and includes the influence of previous factors based on similarity and proximity, ratings for otherwise similar features may exhibit a wide range. The measure returned in the procedure is a "Level of Consistency," ranging from A to F.

Concerns over the methodology appear to be based in part on the "black box" nature of the curves and tables that are utilized, which may lead to conclusions that do not match intuitive expectations about a roadway. The method has not been adopted in a general way.

Fitzpatrick et al.

This speed-based measure has been accepted by FHWA as the basis for examining design consistency on two-lane rural roadways in the IHSDM (*7*). Variations in speed are predicted along an alignment, with warnings issued if speeds vary by more than a set amount from the speed predicted in an upstream roadway segment. The methodology is based on a widely accepted premise that drivers do not expect to have to slow when driving on a roadway segment, and segments that exhibit excessive slowing are expected to perform poorly.

The methodology has been validated in multiple research projects and functions in a manner similar to work being performed in Europe.

The approach seems to be founded on sound principles and a readily observable measure and has been accepted widely by the research community. The weakness of this approach appears to be that few design characteristics significantly influence speed other than horizontal curvature, even though they may be considered to be classic examples of design inconsistencies (e.g., narrow bridges). Although not widely adopted in practice at this point, it is expected that this methodology will be used more generally as IHSDM is implemented.

Alexander and Lunenfeld

Positive Guidance provides a qualitative way to assess the design consistency of a roadway through assessing information needs and expectancy violations (*2*). A set of procedures is provided that assist the engineer in assessing roadways from a driver information viewpoint. The use of checklists and procedures attempts to lead the engineer through the analysis and assists in developing countermeasures.

This procedure attempts to cover design consistency in a broad, global manner and generally accomplishes this task successfully. The procedure has been pilot-tested in a number of studies that are published in the literature, and its principles have been successfully established in the research community. *Positive Guidance* has been used as the basis for sections of the Green Book regarding driver information needs and processing.

SYSTEM STRUCTURE

The proposed expert system on design consistency focuses on recognized consistency issues. The decision to include a particular issue was based on the use of quantifiable measures of those items and their influence on the driver. By basing the system on quantitative, rather than qualitative, measures, the system can be readily included in checks of roadway designs.

In general, design consistency issues or concerns were investigated if they

- Influence driver behavior in a quantifiable manner;
- Are within control of the designer;
- Can be determined from computer aided design and drafting (CADD) data or by user inquiry; and
- Are not checked by the current policy review module (PRM), design consistency module (DCM) (currently based on 85th percentile speed), intersection review module (IRM), or other IHSDM module.

Based on engineering judgment, several general "trigger" levels for judging the presence or influence of a design inconsistency were developed:

- Accident rate increases by 5% or more,
- Speed changes greater than or equal to 5 km/h [3 mph] occur, or
- Lane position changes by more than 0.3 m [1 ft].

Driver workload was also considered, in the form of "Workload increases by X percent or more," but the research team was unable to determine a satisfactory specific trigger or measure. The use of a "system" check was included to provide a check for when multiple features occurring in proximity could be a concern, although workload was not examined directly.

In each case, the trigger level would be used as an aid regarding whether the design inconsistency affected driver performance or behavior; just because a speed change greater than 5 km/h [3 mph] occurs would not determine whether a flag was raised to a designer. These levels are, rather, a guide regarding whether an item should be considered for inclusion in the system. Where appropriate, warning levels corresponding to sight distance level changes of 10 km/h [6 mph] and 25 km/h [16 mph] were used for consistency with the IRM.

The project materials (i.e., rules) developed consist of the following:

1. Rules to identify that a concern is present follow:
   a. The concern and its source should be identified.
   b. Quantitative issues likely to be caught by the policy review or other modules should not be included.
   c. Items should be categorized and like items put together.
   d. Items should be prioritized.
   e. Problems normally should be flagged only if the obvious defect is made worse by another condition.
   f. Concerns should generally be in multiple levels, with expression of the level of concern provided.
   g. Engineering judgment and available literature should be used to identify levels of concern to provide the best available information.
2. Where concerns are present, identify an appropriate solution.
3. Identify complicating factors (e.g., sight distance is probably a common factor for many problems and issues).

Each concern has a model that may be one of the following:

- A formula, an algorithm, etc., leading to a scale.
- A traditional engineering model or new, different model.

Flags may not require a change in the design, but do call attention to an issue. Input data would typically be available in a CADD system, although a user query may be required for some issues (i.e., 85th percentile speed).

A flow chart was developed to provide further information regarding the structure of the expert system being developed (see Figure 1). The chart illustrates how the system will obtain information, process it, interact with the user to evaluate design consistency, and suggest improvements on roadway projects.

Each inconsistency item is being developed to include the following:

- Nature of the problem;
- Applicable model(s);
- Input data needed from CAD or user;
- Threshold values for comparison with designs; and
- Feedback for user
  - Nature of the inconsistency,
  - Influencing factors and their relationship with the feature, and
  - Potential remedial actions or treatments.

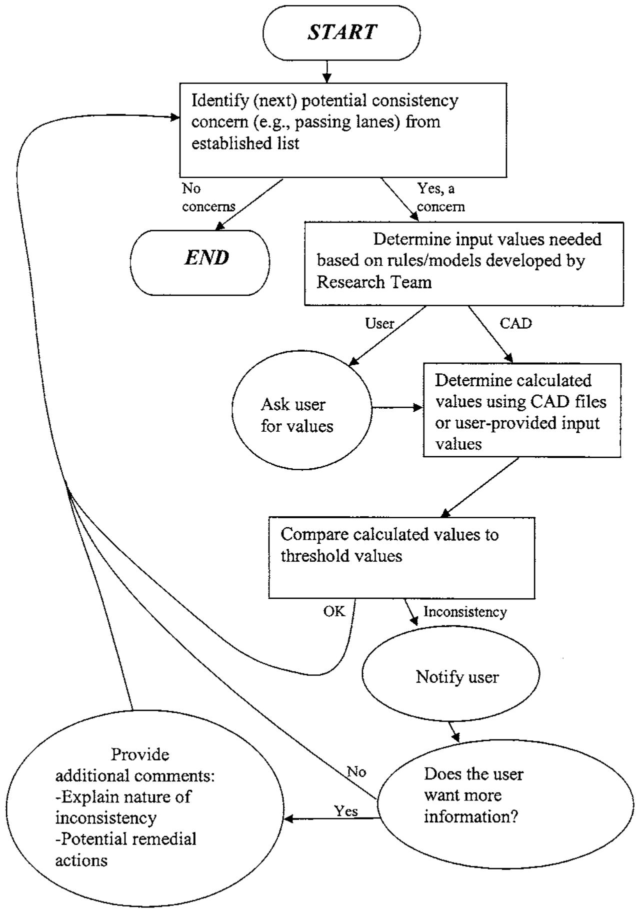


Figure 1. Flow chart showing system structure.

Table 3 lists the names of the consistency rules developed. Items are generally grouped under an area such as "Horizontal Alignment," but issues that involve more than one category are assigned to one particular category to ensure that adequate consideration is made when multiple factors are involved.

These categories clarified the design consistencies considered and provided a framework for the system developed. Individual features were not considered for rating because (1) their presence was thought to be obvious to the designer or (2) their characteristics are generally already measured and evaluated by other material (e.g., the radius for a horizontal curve is already examined by the policy review module).

RULES

1. Rules for Assessing the Consistency of Geometric Features Related to Cross Section

Several cross-section elements (e.g., lane width and shoulder width) clearly influence safety. Changes in those elements violate driver expectancy and increase crash risk. The following rules would be applied to identify inconsistencies related to cross section on two-lane highways for the following conditions:

- Reduction in lane width,
- Reduction in shoulder width,
- Lane drop with major driveway, and
- Major driveway and lane addition.

[The following cross-section inconsistencies are covered under other proposed rules:

- Preview sight distance to reductions in lane width,
- Preview sight distance to reductions in shoulder width,
- Preview sight distance to lane drop,
- Preview sight distance for lane addition, and
- Climbing lane not carried over crest of hill.]

1.1 Reduction in Lane Width

Narrow lanes are associated with increased run-off-the-road, head-on, opposite-direction sideswipe, and same-direction sideswipe accidents. Reductions in lane width associated with a greater than 5% increase in accident risk are flagged as inconsistencies.

The increase in accident risk is based on accident modification factor (AMF) models developed for the IHSDM accident prediction module (*12*) to predict the expected safety performance of rural two-lane highways. The algorithms combined elements of historical accident data, predictions from statistical models, results of before-after studies, and the judgments of experienced engineers. As part of the research, an expert panel of engineers developed AMFs for specific geometric design and traffic control features. The base value of each AMF is 1.0. Any feature associated with a higher accident experience than the base condition has an AMF with a value greater than 1.0, and any feature associated with lower accident experience than the base condition has an AMF with a value less than 1.0.

These factors provide an estimate of the change in accident potential when compared with a base condition. Table 4 provides the models (illustrated in Figure 2). Specific rules for *reduction in lane width* follow.

1.1.1 Level 2 Warning. When AMF is predicted to increase by 5% or more, the following message is displayed to the user:

> *The lane width in the section from XX + XX to YY + YY is Z ft less than in the upstream section. The accident risk associated with lane width is predicted to increase by N percent in this section. Consideration should be given to increasing the lane width.*
>
> *If the lane width cannot be increased, consideration should be given to the use of enhanced markings or signing to alert*

TABLE 3 Rules developed for a design consistency expert system

Cross Section
Reduction in lane width Reduction in shoulder width Lane drop with major driveway Major driveway and lane addition
Horizontal Alignment
Tight horizontal curve with wide shoulders
Vertical Alignment
Steep downgrades
Highway-Railroad Grade Crossings
Highway-Railroad grade crossing with intersection nearby
Bridges
Narrow Bridges
Driveways
Access points or frequency of driveways Minimum separation between driveways Offset opposing driveways
Sight Distance
SSD on the approaches to key roadway features DSD on the approaches to key roadway features
Passing Lanes
Climbing lane needed but not provided Climbing lane not carried over crest Insufficient passing opportunities Passing lane too short Passing lane too long Passing lane addition channels slow vehicles into left lane
Frequency of Decisions on Roadway Segments
Clustering of features: • Intersection • Major driveway • Railroad-highway grade crossing • Beginning or end of a horizontal curve with radius less than 800 m [2,600 ft] • Vertical curve with available SSD less than that given in the Green Book for a design speed equal to 20 km/h [10 mph] less than the roadway operating speed • School zone • Narrow bridge (curb-to-curb width less than the roadway approach including paved shoulder) • Change in posted speed limit • Lane addition • Lane drop • Lane width reduction by 0.6 m [2 ft] or more • Shoulder width reduction by 1.2 m [4 ft] or more

drivers to the narrower lanes. Provision of W5-1 (ROAD NARROWS) signs, edgelines (if none are present), wider edgelines, raised pavement markers on the centerline or edgeline, or roadside delineators should be considered.

1.1.2 Level 1 Warning. When AMF is predicted to increase by 10% or more, the following message is displayed to the user:

The lane width in the section from XX + XX to YY + YY is Z ft less than in the upstream section. The accident risk associated with lane width is predicted to increase by N percent in this section. Strong consideration should be given to increasing the lane width.

If the lane width cannot be increased, consideration should be given to the use of enhanced markings or signing to alert drivers to the narrower lanes. Provision of W5-1 (ROAD NARROWS) signs, edgelines (if none are present), wider edgelines, raised pavement markers on the centerline or edgeline, or roadside delineators should be considered.

1.2 Reduction in Shoulder Width

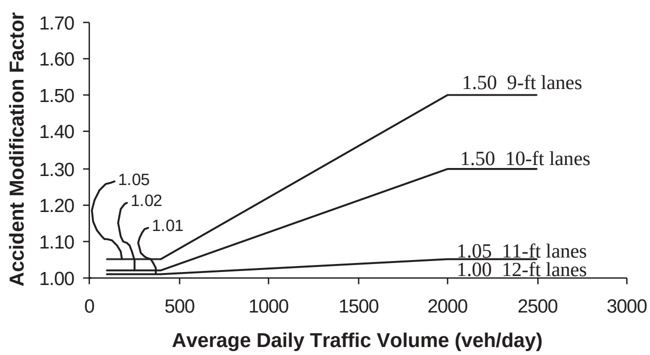
Narrow shoulders are associated with increased single-vehicle run-off-the-road accidents. Reductions in shoulder width that are associated with a greater than 5% increase in accident risk are flagged as inconsistencies.

The increase in accident risk is based on AMF models developed for the IHSDM accident prediction module (*12*). Table 5 provides the base models, as derived from Figure 3.

Changes in the traveled way width to accommodate horizontal curves as described in the AASHTO Green Book (in Exhibits 3-50 through 3-52) should not be considered when evaluating the consistency of shoulder width changes. Specific rules for *reduction in shoulder width* follow.

TABLE 4 Accident modification factor models for lane width (*12*)

Lane Width	Accident Modification Factor		
	ADT<500	500≤ADT≤2000	>2000 ADT
3.6 m [12 ft]	AMF=1	AMF=1	AMF=1
3.3 m [11 ft]	AMF=1.01	AMF=0.000025*ADT+1.0	AMF=1.05
3 m [10 ft]	AMF=1.02	AMF=0.000175*ADT+0.95	AMF=1.30
2.7 m [9 ft]	AMF=1.05	AMF=0.00028*ADT+0.94	AMF=1.50



NOTE: This factor applies to single-vehicle run-off-road, multiple-vehicle same-direction sideswipe accidents, and multiple-vehicle opposite-direction accidents.

Figure 2. Accident modification factors for lane width (12).

1.2.1 Level 2 Warning. When AMF is predicted to increase by 5% or more, the following message is displayed to the user:

The shoulder width in the section from XX + XX to YY + YY is Z ft less than in the upstream section. The accident risk associated with shoulder width is predicted to increase by N percent in this section. Consideration should be given to increasing the shoulder width.

If the shoulder width cannot be increased, consideration should be given to the use of enhanced markings or signing to alert drivers to the narrower shoulders. Provision of edgelines (if none are present), wider edgelines, raised pavement markers on the centerline or edgeline, or roadside delineators should be considered.

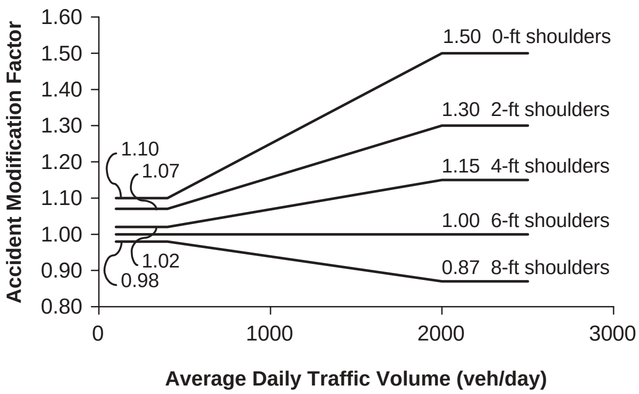
1.2.2 Level 1 Warning. When AMF is predicted to increase by 10% or more, the following message is displayed to the user:

The shoulder width in the section from XX + XX to YY + YY is Z ft less than in the upstream section. The accident risk associated with shoulder width is predicted to increase by N percent in this section. Strong consideration should be given to increasing the shoulder width.

If the shoulder width cannot be increased, consideration should be given to the use of enhanced markings or signing to alert drivers to the narrower shoulders. Provision of edgelines (if none are present), wider edgelines, raised pavement markers on the centerline or edgeline, or roadside delineators should be considered.

TABLE 5 Accident modification factor models for shoulder width (*12*)

Shoulder Width	Accident Modification Factor		
	ADT<500	500≤ADT≤2000	>2000 ADT
2.4 m [8 ft]	AMF=0.98	AMF=-0.000069*ADT+1.0075	AMF=0.98
1.8 m [6 ft]	AMF=1.00	AMF=1.0	AMF=1.00
1.2 m [4 ft]	AMF=1.02	AMF=0.000081*ADT+0.99	AMF=1.15
0.6 m [2 ft]	AMF=1.07	AMF=0.00014*ADT+1.01	AMF=1.30
0 m [0 ft]	AMF=1.10	AMF=0.00025*ADT+1.0	AMF=1.50



NOTE: This factor applies to single-vehicle run-off-road, multiple-vehicle same-direction sideswipe accidents, and multiple-vehicle opposite-direction accidents.

Figure 3. Accident modification factors for shoulder width (12).

1.3 Lane Drop with Major Driveway

Lane drops cause drivers to switch lanes. Erratic maneuvers are more likely in these areas, and drivers may be more likely to leave the roadway through error or in an emergency. Because vehicles exiting the roadway at a driveway slow or stop, driveways should not be located within or immediately downstream of lane drops.

The model compares the distance between the downstream transition point and any driveways within a threshold distance corresponding to the appropriate 85th percentile speed (see Table 6). The table is consistent with AASHTO stopping sight distance values (*6*) reduced by 25 km/h. Any major driveways (left or right side) within either the transition area or the downstream threshold distance from Table 6 will be subject to the warning message below, as appropriate. Because driveways are not always readily movable and may be installed later in the area of the transition anyway, only a Level 2 Warning message is generated. Specific rules for *lane drop with major driveway* follow.

TABLE 6 85th Percentile speed versus driveway threshold distance (*6*)

85th Percentile Speed, km/h	Driveway Threshold Distance, m
50	25
60	38
70	55
80	73
90	94
100	117
110	142
120	170
130	199
Note: 1 km/h = 0.62 mph, 1 m = 3.28 ft	

1.3.1 Level 2 Warning. Either (1) a left- or right-hand driveway is present within the transition area and is within the clear zone or (2) the distance between the end transition point and a left- or right-hand driveway corresponds to driveway threshold distances provided in Table 6. Figure 4 illustrates the areas of concern. The following message will be displayed to the user:

Consideration should be given to either moving the driveway at station XX + XX or moving the lane drop transition so the driveway is not in the lane drop transition or within Z [table value corresponding to 85th percentile SSD value] of the transition.

1.4 Major Driveway and Lane Addition

The presence of a major (i.e., high-volume) driveway in the area of a lane addition may be associated with an increase in crash risk. A lane addition is a maneuver point, and drivers may not be expecting a vehicle to slow down to enter a driveway immediately prior to the introduction of a lane. Specific rules for *major driveway and lane addition* follow.

1.4.1 Level 2 Warning. When a major driveway is located in the area of concern, the following message is displayed to the user:

The location of major driveways in lane addition areas may be associated with an increased risk of crash. Consideration should be given to extending the auxiliary lane so the driveway at station XX + XX is not located in the transition area or relocating the driveway.

2. Rule for Assessing the Consistency of Geometric Features Related to Horizontal Alignment

The following rule would be applied to identify inconsistencies related to horizontal alignment on two-lane highways for the following condition:

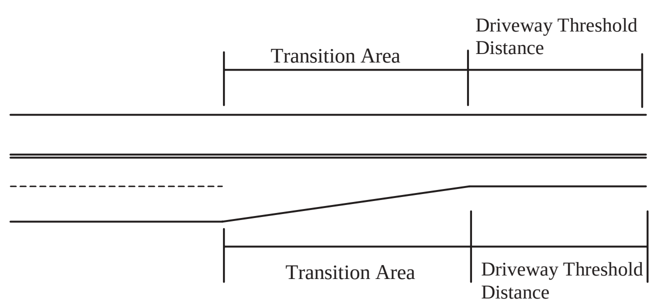


Figure 4. Areas of concern for driveways near lane drop.

- Tight horizontal curve with wide shoulders.

This rule is discussed below.

[The following horizontal alignment inconsistencies are covered under other IHSDM modules:

- Intersection on horizontal curve—Intersection Design Review Module (IDRM);
- Sequence of curves and tangents (e.g., sharp curve following gentle curve and sharp curve after long tangent)—Speed Consistency;
- Intersecting roads along projecting tangents—IDRM; and
- Tangent to curve transition—Speed Consistency.

The following horizontal alignment inconsistency is covered under other design consistency rules:

- Driveway on horizontal curve—Sight Distance Rule.]

2.1 Tight Horizontal Curve with Wide Shoulders

On tight horizontal curves, drivers need to drive more slowly, while wide shoulders or lanes permit higher speeds. The combination of tight horizontal curves with wide shoulders or lanes provides an inconsistent message to drivers. The findings from the FHWA Design Inconsistency project can provide the basis for a rule to check for locations with tight horizontal curves and wide shoulders or lanes. Tight horizontal curves could be defined based on the amount of speed reduction they would cause (which the design consistency module could provide) or they could be defined as being below a set radius value, such as 800 m [2,600 ft] or 250 m [800 ft]. When a radius is 800 m [2,600 ft] or greater, the operating speeds on a horizontal curve are very similar to speeds on long tangents (*7*). Operating speeds on horizontal curves with less than an 800-m [2,600-ft] radius decrease with decreases in radius lengths and drop sharply when the radius is less than 250 m [800 ft] (*7*). The *Prediction of the Expected Safety Performance of Rural Two-Lane Highways* FHWA report uses 3.6-m [12-ft] lanes and 1.8-m [6-ft] shoulders as the nominal or base condition (*12*). In consideration of the practice of pavement widening on horizontal curves for trucks, this rule will check for changes in shoulder width between the tangent and the horizontal curve in excess of the values listed in the Green Book Exhibits 3-51 and 3-52 (*6*). The Green Book Exhibit 3-51 uses radius of curve, design speed, and roadway width to determine the traveled way widening for a WB-15 (WB-50) design vehicle. Exhibit 3-52 provides the adjustments for other design vehicles.

An inconsistency should be flagged when the following conditions exist:

- Design consistency module determines that a speed change >5 km/h [3 mph] exists and
- Shoulder width is greater on the curve than upstream segment by an amount that is greater than the value listed in Exhibit 3-51 for WB-50 vehicles (or adjusted by the value in Exhibit 3-52 if other design vehicle is preferred).

Specific rules for *tight horizontal curve with shoulders* follow.

2.1.1 Level 2 Warning. The following message could be displayed:

> *The horizontal curve at station XX + XX is a tight horizontal curve (with an associated speed reduction of ZZ). Its shoulder width of BB is greater than the upstream shoulder width by an amount that is greater than the amount of traveled way widening listed in the Green Book for the given radius, design speed, and roadway width. This combination provides a mixed message to the driver.*
>
> *Potential treatments for the horizontal curve include chevrons and upstream warning signs posted according to the Manual on Uniform Traffic Control Devices (MUTCD).*

3. Rule for Assessing the Consistency of Geometric Features Related to Vertical Alignment

The following rule would be applied to identify inconsistencies related to vertical alignment on two-lane highways for the following condition:

- Steep downgrades.

This rule is discussed below.

[The following vertical alignment inconsistency is covered under other IHSDM modules:

- Intersection on crest curve—IDRM.]

3.1 Steep Downgrades

The MUTCD requirements for the Hill (W7-1) sign are the criteria suggested for use to determine when a downgrade should be a concern. Specific rules for *steep downgrades* follow.

3.1.1 Level 2 Warning. The IHSDM should flag a warning when the following conditions exist:

- 5% downgrade that is more than 900 m [3,000 ft] in length,
- 6% downgrade that is more than 600 m [2,000 ft] in length,

- 7% downgrade that is more than 300 m [1,000 ft] in length,
- 8% downgrade that is more than 225 m [750 ft] in length, or
- 9% downgrade that is more than 150 m [500 ft] in length.

The following message could be displayed:

The downgrade(s) between station XX + xx and XX + xx has a length and percent grade that require special precautions on the part of the road user. The MUTCD states that a Hill (W7-1) sign (either alone or in combination with a supplemental grade (W7-3) plaque) should be used in advance of downgrades with a y% grade that is more than zzz meters in length.

4. Rules for Assessing the Consistency of Geometric Features Related to Highway-Railroad Grade Crossings

The following rule would be applied to identify inconsistencies related to horizontal alignment on two-lane highways for the following condition:

- Highway-railroad grade crossing with intersection nearby.

This rule is discussed below.

[The following horizontal alignment inconsistency is covered under other design consistency rules:

- Preview sight distance to highway-railroad grade crossing—Sight Distance Rule.]

4.1 Highway-Railroad Grade Crossing with Intersection Nearby

Railroad grade crossings with nearby intersections are relatively common. If the intersection has traffic control that requires stopping on the approach leg with the railroad grade crossing, the intersection should be reviewed to determine whether intersection sight distance is adequate at vehicle stop positions. Those grade crossings with insufficient room to store design vehicles between the intersections and the grade crossing may present drivers with a difficult driving decision: stop prior to the grade crossing or stop at the intersection while blocking the grade crossing. Adequate sight distance should be available at the point where the driver should stop.

A comparison is made of the clear distance between the highway intersection and the railroad grade crossing to the length of the design vehicle plus a margin (see Table 7); if inadequate storage room is available, intersection sight distance checks should be made from the stop bar prior to the highway-railroad grade crossing.

For those locations without sufficient clearance for the selected design vehicle, the appropriate intersection sight distance values should be computed from AASHTO models (shown in cases A-F in the AASHTO Green Book beginning on page 658) for all permitted movements from the approach leg in question, computed from the highway-railroad grade crossing stop line. Specific rules for *highway-railroad grade crossing with intersection nearby* follow.

4.1.1 Level 1 Warning. This warning is provided when insufficient room is available to store the design vehicle (Z) and insufficient intersection sight distance is available from the stop bar prior to the highway-railroad grade crossing. The following message could be displayed:

TABLE 7 Design vehicle dimensions (*6*)

Design Vehicle	Length (m)	Margin (m)	Total Space Required (m)
Passenger car PC	5.8	3	8.8
Single unit truck SU	9.2	3	12.2
Inter-city bus BUS-12	12.2	3	15.2
Conventional school bus (65 passenger) S-Bus 11	10.9	3	13.9
Large school bus (84 passenger) S-Bus 12	12.2	3	15.2
Articulated bus A-BUS	18.3	3	21.3
Intermediate semitrailer WB-12	13.9	3	26.9
Intermediate semitrailer WB-15	16.8	3	19.8
Interstate semitrailer WB-19	20.9	3	23.9
Interstate semitrailer WB-20	22.4	3	25.4
“Double-Bottom”-semitrailer/trailer WB-20D	22.4	3	25.4
Triple-semitrailer/trailers WB-30T	32.0	3	35.0
Motor Home MH	9.2	3	12.2
Car and camper trailer	14.8	3	17.8
Car and boat trailer	12.8	3	15.8
Motor home and boat trailer	16.2	3	19.2
Farm tractor	4.9	3	7.9
Note: 1 m = 3.28 ft			

Storage space between the intersection at station XX + XX and the highway-railroad grade crossing at station YY + YY is inadequate to store the design vehicle (Z) and intersection sight distance is inadequate prior to the highway-railroad grade crossing.

More storage space is recommended to permit storage between the highway intersection and the highway-railroad grade crossing or the available intersection sight distance upstream of the grade crossing should be increased to meet or exceed requirements. If providing more storage space is impractical storage space signing should be provided as recommended in the MUTCD. If the intersection is signalized, consideration should be given to providing an advance traffic signal prior to the highway-railroad grade crossing that is coordinated with the traffic signal at the intersection.

5. Rules for Assessing the Consistency of Geometric Features Related to Narrow Bridges

A narrow bridge provides less recovery room, with potential for impact with barrier or opposing vehicles. When sight distance is inadequate, drivers may arrive at the bridge at higher speeds than they would be comfortable, given the bridge width. For single-lane bridges, the sight distance should be adequate for a driver to come to a complete stop prior to crossing the bridge. The following rule would be applied to identify inconsistencies related to narrow bridges on two-lane highways:

- Sight distance to a narrow bridge.

This rule is discussed below.

5.1 Sight Distance to a Narrow Bridge

For the purposes of these rules, three categories of narrow bridges have been identified (*13*):

- Restricted Width (R.W.): If a bridge's width is less than 7.3 m [24 ft] OR if it is less than the approach cross-section width, it should be considered a "restricted width" bridge.
- Low-Volume Single-Lane (L.S.): If a bridge's width is less than 5.5 m [18 ft], it should be considered a single-lane bridge. A single-lane bridge with ADT < 400 vehicles per day (vpd) is defined as a low-volume single-lane bridge.
- High-Volume Single Lane (H.S.): It is a single-lane bridge with ADT > 400 vpd.

There are no models available for directly predicting operating speed or desired speed at a narrow bridge. Thus, it is assumed that the speed prediction factors used in the HCM 2000 for two-lane highway analysis can be used to predict speeds on two-lane bridges as a function of lane width reduction. It is stated in the HCM that base free-flow speed (FFS) should reflect the character of the study facility in terms of alignment and traffic conditions; however, no specific guidance is provided for estimating it. Adjustment factors were identified using the factors from the HCM 2000 (see Table 8).

The procedure for checking inconsistency is as follows:

1. Estimate or input the speed at the bridge.

   R.W.: Speed estimated as shown in Equation 1 below.
   L.S.: Speed = 0 mph (to allow the vehicle to stop, if there is another vehicle arriving from the opposite direction).
   H.S.: Speed = 0 mph (to allow a vehicle to stop prior to the bridge).

   Using the HCM 2000 models, the speed at a narrow bridge can be estimated as follows:

$$\text{Speed at Bridge (FFS)} = \text{BFFS} - f_{LS}, \quad (1)$$

where

TABLE 8 Adjustment (f_{LS}) for lane width and shoulder width (*14*)

Lane Width, LW (m)	f_{LS} (km/h)			
	Shoulder Width, SW (m)			
	$0 \le SW < 0.6$	$0.6 \le SW < 1.2$	$1.2 \le SW < 1.8$	$SW \ge 1.8$
$2.7 \le SW < 3.0$	10.3	7.7	5.6	3.5
$3.0 \le SW < 3.3$	8.5	5.9	3.8	1.7
$3.3 \le SW < 3.6$	7.5	4.9	2.8	0.7
$LW \ge 3.6$	6.8	4.2	2.1	0.0

Note: 1 m = 3.28 ft and 1 km/h = 0.62 mph

FFS = estimated free-flow speed
BFFS = base free-flow speed
f_{LS} = adjustment for lane width and shoulder width, from HCM 2000 Exhibit 20-5

The BFFS can be obtained based on the 85th percentile operating speed at the approaching segment and will be estimated as follows:

(1) If the approaching segment has lanes equal to or wider than 3.6 m [12 ft] and shoulders equal to or wider than 1.8 m [6 ft], then the BFFS = 85% approach operating speed.
(2) If the approaching segment has lanes narrower than 3.6 m [12 ft] OR shoulders narrower than 1.8 m [6 ft], then:

$$\text{BFFS} = \text{85th percentile approach operating speed} + f_{LS} \text{ for the approaching segment.} \quad (2)$$

Thus, the speed at the bridge can be estimated as follows:

$$\begin{aligned}\text{Speed at Bridge (FFS)} &= \text{Base FFS} \\ &\quad - f_{LS} \text{ for the bridge} \\ &= \text{85\% approach operating speed} \\ &\quad + f_{LS} \text{ for the approaching segment} \\ &\quad - f_{LS} \text{ for the bridge.}\end{aligned} \quad (3)$$

2. Estimate or input the speed at the approaching segment.

Estimate deceleration distance, assuming a deceleration rate of 1.0 m/s^2 [3.28 ft/s^2] (the maximum value provided by the model developed (*7*)). If the deceleration distance is lower than sight distance, no further action is required.

If the deceleration distance is equal to or greater than the sight distance, an inconsistency has been detected and the warning message should be displayed.

Specific rules for *sight distance to a narrow bridge* follow.

5.1.1 Level 1 Warning. The following message would be displayed for an R.W. bridge with limited sight distance:

The bridge at station XXX + XX has been found to be a potential safety concern because of its width and sight distance. Factors in this determination include bridge width, approach lane width, speed on the approach, and sight distance.

Warning signs (Narrow Bridge) should be used as appropriate (see MUTCD for further information).

The following message would be displayed for an L.S. bridge with limited sight distance:

The bridge at station XXX + XX has been found to be a potential safety concern because of its width and sight distance. Factors in this determination include bridge width, approach lane width, speed on the approach, and sight distance.

Warning signs (Single-Lane Bridge) should be used as appropriate (see MUTCD for further information).

5.1.2 Level 2 Warning. The following message would be displayed for an H.S. bridge with limited sight distance:

The bridge at station XXX + XX has been found to be a potential safety concern because of its width and sight distance. Its relatively high ADT has contributed to this "Level 2" Warning. Factors in this determination include bridge width, approach lane width, speed on the approach, and sight distance.

Warning signs (Single-Lane Bridge) should be used as appropriate (see MUTCD for further information).

6. Rules for Assessing the Consistency of Geometric Features Related to Driveways

The following rules would be applied to identify design inconsistencies related to driveways:

- Access points or frequency of driveways—Speed Differential;
- Access points or frequency of driveways—Accident Potential;
- Minimum separation between driveways; and
- Offset opposing driveways.

Each of these rules is discussed below.

6.1 Access Points or Frequency of Driveways—Speed Differential

Driveways located along a two-lane highway are believed to affect the traffic operation along the facility adversely. As vehicles enter and leave the major roadway at driveways, conflicts occur because of differences in speeds between through and turning traffic. These speed differences cause friction in the traffic stream and consequently affect the travel speeds along the roadway. The conflicts resulting from speed differentials may also result in crashes, adversely affecting the safety along the roadway. The following procedures describe methodologies to evaluate the consistency of a design based on the difference in operating speeds and the potential for an increase in accidents between adjacent roadway segments due to differences in driveway densities.

Currently, no speed prediction models consider the effect of driveway density on operating speed. In the absence of such information, it is recommended that the methodology provided in the HCM 2000 on estimating free-flow speed on two-lane highways be used to predict the difference in operating speeds between adjacent roadway segments on two-lane highways (*14*). The methodology in the HCM 2000 adjusts a base level free-flow speed, taking into consideration lane width and shoulder width and the number of access points (driveways), to estimate the free-flow speed along the roadway:

$$FFS = BFFS - f_{LS} - f_A, \quad (4)$$

where

FFS = estimated free-flow speed
BFFS = base free-flow speed
f_{LS} = adjustment for lane width and shoulder width, from HCM 2000 Exhibit 20-5
f_A = adjustment for access points, from HCM 2000 Exhibit 20-6

Assuming that the lane widths along the two-lane highway are greater than 3.6 m [12 ft] and the shoulders widths are greater than 1.8 m [6 ft], the adjustment factor for lane width and shoulder width equals zero, and equation 1 simplifies to the following:

$$FFS = BFFS - f_A. \quad (5)$$

The adjustment factor for access-point density (f_A) is provided in Exhibit 20-6 of the HCM 2000 and is reproduced in Table 9. Table 9 indicates that each access point per kilometer decreases the estimated free-flow speed by approximately 0.67 km/h [0.4 mph].

Thus, if a roadway segment has at least eight driveway access points per kilometer more than the previous segment, an inconsistency in design occurs because of a reduction in operating speed of at least 4.8 km/h [3 mph].

Note that the adjustment factors for access-point density were developed based on the number of access points along the right side of the roadway. Thus, the access-point density for a roadway is found by dividing the total number of access points (intersections and driveways) on the right side of the roadway by the length of the section in kilometers. An intersection or driveway should be included in the determination of access-point density only if it is considered to have a significant influence on traffic flow (*14, 15*). Intersections or driveways that are difficult for the driver to identify or where there is little activity should not be included in the determination of access-point density. For example, private driveways to individual residences or service driveways at commercial sites might not be included in the determination of access-point density. If access points on the opposite (left) side of the roadway are expected to have a significant effect on traffic flow in the direction of interest, these intersections and driveways may be included in the determination of access-point density.

TABLE 9 Adjustment (f_A) for access-point density (*14*)

Access Points per Kilometer	Reduction in FFS (km/h)
0	0.0
6	4.0
12	8.0
18	12.0
≥ 24	16.0
Note: 1 km = 0.62 mi	

Specific rules for *access points or frequency of driveways—speed differential* follow.

6.1.1 Level 2 Warning. If a roadway segment has at least eight driveway access points per kilometer more than the previous segment, an estimated speed differential greater than or equal to 5 km/h [3 mph] will occur. The following message to the user should be displayed:

The number of driveway access points between Stations XXX + XXX and YYY + YYY may lead to operational inconsistencies. Using the HCM 2000 procedures for two-lane highways, an investigation of the difference in estimated operating speeds between the approaching segment (Stations AAA + AAA to BBB + BBB) and the segment between Stations XXX + XXX and YYY + YYY is recommended.

Consideration should be given to decreasing the number of driveway access points between Stations XXX + XXX and YYY + YYY.

6.1.2 Level 1 Warning. If a roadway segment has at least 16 driveway access points per kilometer more than the previous segment, an estimated speed differential greater than or equal to 10 km/h [6 mph] will occur. The following message to the user should be displayed:

The number of driveway access points between Stations XXX + XXX and YYY + YYY may lead to operational inconsistencies. Using the HCM 2000 procedures for two-lane highways, an investigation of the difference in estimated operating speeds between the approaching segment (Stations AAA + AAA to BBB + BBB) and the segment between Stations XXX + XXX and YYY + YYY is recommended.

Strong consideration should be given to decreasing the number of driveway access points between Stations XXX + XXX and YYY + YYY.

6.2 Access Points or Frequency of Driveways—Accident Potential

The accident prediction algorithm for roadway segments incorporated an AMF for driveway density. The base condition for driveway density is three driveways per kilometer. The expert panel decided on the following AMF for driveway density:

$$AMF = \frac{0.2 + [0.05 - 0.005\ln(ADT)](1.6093)(DD)}{0.2 + [0.05 - 0.005\ln(ADT)](5)} \quad (6)$$

where

ADT = annual average daily traffic volume of the roadway segment being evaluated (veh/day); and
DD = driveway density (driveways per kilometer).

The AMF is derived from the work of Muskaug (*16*). The expert panel considered the Norwegian study to be the best available study on the safety effects of driveway density on rural two-lane highways.

Specific rules for *access points or frequency of driveways—accident potential* follow.

6.2.1 Level 2 Warning. If the difference between the AMFs for the roadway segment being evaluated (AMF_2) and the previous segment (AMF_1) is greater than or equal to 0.05, an estimated accident rate increase of 5% or more will occur. The following message to the user should be displayed:

The number of driveway access points between Stations XXX + XXX and YYY + YYY is a potential concern. An investigation of the expected change in accidents between the approaching segment (Stations AAA + AAA to BBB + BBB) and the segment between Stations XXX + XXX and YYY + YYY is recommended.

6.2.2 Level 1 Warning. If the difference between the AMFs for the roadway segment being evaluated (AMF_2) and the previous segment (AMF_1) is greater than or equal to 0.10, an estimated accident rate increase of 10% or more will occur. The following message to the user should be displayed:

The number of driveway access points between Stations XXX + XXX and YYY + YYY is a potential concern. An investigation of the expected change in accidents between the approaching segment (Stations AAA + AAA to BBB + BBB) and the segment between Stations XXX + XXX and YYY + YYY is recommended.

6.3 Minimum Separation Between Driveways

The objective of access management is to reduce the frequency of conflicts by separating adjacent conflict areas and limiting the number of conflict points per length of highway. It is expected to reduce the severity of rear-end collisions, because it allows more deceleration distance and perception time for motorists. The distance between driveways must allow driveway vehicles to safely accelerate, decelerate, and cross traffic streams without excessive interference with through traffic or traffic using adjacent driveways. Traffic volumes at residential driveways and field entrances are typically low, however, so the separation distances recommended are applicable to commercial and high-volume driveways. Table 10 shows the recommended minimum spacing based on normal acceleration and deceleration rates for various highway speeds.

Specific rules for *minimum separation between driveways* follow.

6.3.1 Level 2 Warning. The spacing between each pair of adjacent driveways on each side of the proposed roadway should be reviewed. If the spacing is less than the recommended value from Table 10, the following message to the user should be displayed:

The spacing between the driveways at Stations XXX + XXX and YYY + YYY on the Z side of the road may be too small.

6.4 Offset Opposing Driveways

The objective of offsetting opposing driveways (i.e., driveways on opposite sides of the roadway) is to limit the number of conflict points. The separation distance better facilitates driveway-to-driveway maneuvers and may alleviate the concentrated conflict area that is present with opposing driveways. However, offsetting opposing driveways will cause an increase in the number of turning and weaving maneuvers.

TABLE 10 Minimum separation of adjacent driveways (*10*)

Highway Speed (km/h)	Rate of Deceleration (m/s^2)	Rate of Acceleration (m/s^2)	Minimum Spacing (m)
32	2.6	0.9	30
40	2.6	0.8	32
48	2.6	0.6	38
56	2.6	0.5	46
64	2.6	0.5	56
72	2.6	0.5	70
80	2.6	0.5	84

Note: 1 km = 0.62 mi
1 m/s^2 = 3.28 ft/s^2
1 m = 3.28 ft

One of the most important design considerations in offsetting opposing driveways is the separation distance between the two driveways. This distance should be large enough so that the motorist can make a definite turn onto the roadway and then turn into the other driveway, thus preventing diagonal crossing movements. Driveways spaced too close together may also cause some movements to be blocked by left-turn queues at the approach to the other driveway. Glennon et al. recommend a minimum driveway separation of 90 m [300 ft] (*17*).

For offset opposing driveways spaced too close together, an obvious treatment is to relocate one of the driveways such that the separation distance between the two driveways is increased. However, an alternative to increasing the separation distance is to relocate the driveways directly opposite each other, thus allowing crossing movements without entering the major road. Traffic volumes at residential driveways and field entrances are typically low, however, so the offset distances recommended are applicable to commercial and high-volume driveways.

Specific rules for *offset opposing driveways* follow.

6.4.1 Level 2 Warning. Each pair of offset opposing driveways on the proposed roadway should be reviewed. If the separation distance is less than 90 m [300 ft], the following message to the user should be displayed:

> *The separation distance between the offset opposing driveways at Stations XXX + XXX and YYY + YYY may be too short to provide sufficient weaving distance and left-turning storage length. The driveways should either be located opposite one another or should be offset by at least 90 m [300 ft].*

7. Rules for Assessing the Consistency of Geometric Features Related to Sight Distance

A driver's ability to see ahead is important in the safe and efficient operation of a vehicle on the roadway (*6*). At a minimum, all roadways should provide adequate stopping sight distance, the sight distance needed for a below-average driver to safely stop a vehicle traveling at or near the design speed before reaching a stationary object in its path. However, when drivers must make complex or instantaneous decisions because information is difficult to perceive or an unexpected maneuver is required, sight distances greater than those needed for stopping are recommended. In these complex or unexpected situations, decision sight distance (DSD) provides the greater visibility distance that drivers need and is defined as the distance needed for a driver to detect an unexpected or otherwise difficult-to-perceive information source or condition in a roadway environment that may be visually cluttered, recognize the condition or its potential threat, select an appropriate speed and path, and initiate and complete the maneuver safely and efficiently. DSD values are substantially greater than SSD values, offering drivers a greater margin for error and affording them sufficient visibility to maneuver their vehicles at the same or reduced speed rather than coming to a complete stop. The availability of adequate SSD at all locations on the roadway is checked by the IHSDM Policy Review Module (PRM). These design consistency procedures focus on SSD and DSD on approaches to key roadway features. The following design consistency rules based on sight distance are presented below:

- SSD on the approaches to key roadway features and
- DSD on the approaches to key roadway features.

7.1 SSD on the Approaches to Key Roadway Features

Evaluating SSD on the approaches to key roadway features involves comparing the available SSD to threshold values that trigger advisory messages to the user. The key features at which SSD-based rules are applied include the following:

- School zones,
- Passing/climbing lane drops,
- Narrow bridges,
- Lane width reductions,
- Shoulder width reductions,
- Railroad-highway grade crossings, and
- Major driveways.

The available sight distance used in applying the SSD-based rules is the distance at which the feature in question can be seen by a driver with an eye height of 1,080 mm [3.5 ft]. The object heights used in applying the SSD-based rules vary with the feature to be seen, but are never greater than the 600-mm [2.0-ft] object height used in SSD design. The object heights used for specific features are as follows:

- School zones—600 mm [2 ft];
- Passing/climbing lane drops—0 mm [0 ft];
- Narrow bridges—600 mm [2 ft];
- Lane width reductions—0 mm [0 ft];
- Shoulder width reductions—0 mm [0 ft];
- Railroad-highway grade crossings—0 mm [0 ft]; and
- Major driveways—600 mm [2 ft].

A narrow bridge is defined as a bridge whose curb-to-curb width is less than the traveled way plus paved shoulder width on the approach to the bridge. Available sight distance should be determined in a three-dimensional analysis using procedures already developed for the IHSDM PRM. A major driveway is defined as a driveway with a large number of entering and exiting vehicles (e.g., shopping center or "big box" retail development)

The threshold values that trigger advisory messages to the user are intended to identify situations that should be of potential concern to designers. As in the FHWA Intersection Diagnostic Review Module, these messages should be triggered for sight distance values below the actual or anticipated 85th percentile speed of the facility (*18*).

The general SSD model used to determine these threshold values is as follows:

$$SSD = 0.278Vt + \frac{V^2}{254\left(\left(\frac{a}{9.81}\right)+G\right)} \qquad (7)$$

where

SSD = stopping sight distance (m)
t = brake reaction time (2.5 s)
V = 85th percentile operating speed (km/h)
a = deceleration rate (3.4 m/s^2 [11.2 ft/s^2])
G = local percent grade divided by 100 (+ for upgrades, – for downgrades)

Specific rules for *SSD on the approaches to key roadway features* follow.

7.1.1 Level 1 and 2 Warnings. Level 1 and Level 2 advisory messages should be triggered when available sight distance falls below the values computed with the following equation:

$$SSD_{threshold} = 0.278(V-X)t + \frac{(V-X)^2}{254\left(\left(\frac{a}{9.81}\right)+G\right)} \qquad (8)$$

where

X = specified speed reduction value from Table 11.

The advisory message generated when $SSD_{available} < SSD_{threshold}$ should be as follows:

> *The available stopping sight distance (SSD) on the approach to the [state type of roadway feature] in the section from XXX + XXX to YYY + YYY is less than desirable to allow a motorist to slow or stop before reaching the specified location. The design should be checked to determine if the vertical alignment can be realigned or the object causing the sight obstruction can be relocated or removed to improve a driver's sight line on the approach to the roadway feature.*

7.2 DSD on the Approaches to Key Roadway Features

Evaluating DSD on the approaches to key roadway features involves comparing the available sight distance to $DSD_{threshold}$ values that trigger advisory messages to the user. The key features at which DSD-based rules are applied include the following:

- School zones,
- Passing/climbing lane drops, and
- Railroad-highway grade crossings.

The available sight distance used in applying the DSD-based rules is the distance at which the feature in question can be seen by a driver with an eye height of 1,080 mm [3.5 ft]. The object heights used in applying the DSD-based rules vary with the feature to be seen. The object heights used for specific features are as follows:

- School zones—600 mm [2 ft];
- Passing/climbing lane drops—0 mm [0 ft]; and
- Railroad-highway grade crossings—0 mm [0 ft].

A narrow bridge is defined as a bridge whose curb-to-curb width is less than the traveled way plus paved shoulder width on the approach to the bridge. Available sight distance should be determined in a three-dimensional analysis using procedures already developed for the IHSDM PRM.

The threshold values that trigger advisory messages to the user are intended to identify situations that should be of potential concern to designers. $DSD_{threshold}$ values should be calculated from the anticipated 85th percentile speed of the facility. When evaluating DSD on the approaches to key roadway features, the type of avoidance maneuver required needs to be considered. On the approach to a school zone and to a passing/climbing lane drop, a speed/path/direction change will most often be the appropriate maneuver. At a railroad-highway grade crossing, the required maneuver is a complete stop.

The general DSD models used to determine threshold values are as follows:

Avoidance Maneuver: Speed/path/direction change

$$DSD = 0.278Vt \qquad (9)$$

TABLE 11 Specified speed reduction values used in determining threshold values of sight distance

ADT Level	Specified Speed Reduction (X)	
	Level 1 Advisory	Level 2 Advisory
≥ 5,000 veh/day	10 km/h	0
< 5,000 veh/day	25 km/h	0
Note: 1 km = 0.62 mi		

Avoidance Maneuver: Stop

$$DSD = 0.278Vt + 0.039\frac{V^2}{a} \tag{10}$$

where

DSD = decision sight distance
V = speed (km/h)
t = reaction time (s)
a = deceleration rate (m/s^2)

Specific rules for *DSD on the approaches to key roadway features* follow.

7.2.1 Level 2 Warning. When the required maneuver is a speed/path/direction change such as on the approach to a school zone or a passing/climbing lane drop, a Level 2 advisory message should be triggered when available sight distance falls below $\text{DSD}_{\text{threshold}}$ values computed with the following equation:

$$DSD_{threshold} = 0.278Vt. \tag{11}$$

For speed/path/direction changes on rural roads, a recommended value for t is between 10.2 and 11.2 s.

When the required maneuver is bringing the vehicle to a complete stop such as on the approach to a railroad-highway grade crossing, a Level 2 advisory message should be triggered when available sight distance falls below $\text{DSD}_{\text{threshold}}$ values computed with the following equation:

$$DSD_{threshold} = 0.278Vt + 0.039\frac{V^2}{a}. \tag{12}$$

A value of 3.0 s for t should be used for estimating $\text{DSD}_{\text{threshold}}$ when a stopping maneuver is required.

The advisory message generated when the available sight distance is less than $\text{DSD}_{\text{threshold}}$ should be:

> *The available sight distance on the approach to the* <u>*[state type of roadway feature]*</u> *in the section from XXX + XXX to YYY + YYY is less than the desirable decision sight distance (DSD). The design should be checked to determine if the vertical alignment can be realigned or the object causing the sight obstruction can be relocated or removed to improve a driver's sight line on the approach to the roadway feature.*

8. Rules for Assessing the Consistency of Geometric Features Related to Passing Demands and Opportunities

The following rules would be applied to identify inconsistencies related to passing demands and opportunities on two-lane highways:

- Climbing lane needed but not provided,
- Climbing lane not carried over crest,
- Insufficient passing opportunities,
- Passing lane too short,
- Passing lane too long, and
- Passing lane addition channels slow vehicles into left lane.

Each of these rules is discussed below.

[The following related rules are presented elsewhere:

- SSD on approaches to passing/climbing lane drops and
- DSD on approaches to passing/climbing lane drops.]

8.1 Climbing Lane Needed but Not Provided

The general warrant for provision of a climbing lane on a two-lane highway is presented in the AASHTO Green Book (*6*). For a climbing lane to be warranted, the following three conditions must be met:

1. Upgrade traffic flow rate in excess of 200 vehicles per hour (vph);
2. Upgrade truck flow rate in excess of 20 vph; and
3. One of the following conditions exists:
   - A 15 km/h [10 mph] or greater speed reduction is expected for a typical heavy truck.
   - Level-of-service E or F exists on the grade.
   - A reduction of two or more levels of service is experienced when moving from the approach segment to the grade.

Conditions 1 and 2 can be easily determined for available data or by a query to the user. Condition 3 is more complicated because both the truck speed profile and the level of service for the approach segment and the grade must be assessed.

A recent FHWA report, *The Capability and Enhancement of VDANL and TWOPAS for Analyzing Vehicle Performance on Upgrades and Downgrades within IHSDM* (*19*) presents a detailed description of automated procedures for assessing Conditions 1 through 3. The automated procedures involve application of the TWOPAS model (the state-of-the-art computer simulation model for two-lane highways).

Specific rules for *climbing lane needed but not provided* follow.

8.1.1 Level 2 Warning. If the three conditions listed above are all met, a warning should be issued to the user:

> *Upgrade from Station XX + XXX to YY + YYY warrants a climbing lane, but no climbing lane is provided.*

8.2 Climbing Lane Not Carried Over Crest

Climbing lanes are most effective, and presumably operate most safely, where the climbing lane is carried over the crest of an upgrade and the lane drop occurs on the subsequent downgrade. This provides an opportunity for heavy trucks to recover some of their lost speed before merging with faster traffic.

As a general guideline, it is recommended that the beginning of the lane drop taper be placed at least 300 m [1,000 ft] downstream of the crest. Desirably, DSD should be provided to the beginning of the lane drop.

Specific rules for *climbing lane not carried over crest* follow.

8.2.1 Level 2 Warning. This rule is recommended as follows:

For a climbing lane in the direction of increasing stations, if

$$(\text{Station}_{\text{begin lane drop}} - \text{Station}_{\text{crest}}) < 300 \text{ m } [1{,}000 \text{ ft}]$$

or for a climbing lane in the direction of decreasing stations, if

$$(\text{Station}_{\text{begin lane drop}} - \text{Station}_{\text{crest}}) > -300 \text{ m } [-1{,}000 \text{ ft}]$$

then display the following message to the user:

> *Climbing lane drop for YY traffic at Station XXX + XX is not carried over the crest of the grade. Safer and more efficient operations should result if the climbing lane is carried over the crest and dropped on the downgrade.*

This test could be refined to incorporate a test for the local grade at the beginning of the lane drop taper. If, for example, this point was located on an upgrade of 2% or more, a message like the following could be displayed for the user:

> *The local grade at the climbing lane drop for YY traffic at Station XXX + XX is located on an upgrade. Safer and more efficient operations should result if the climbing lane is carried over the crest and dropped on the downgrade.*

8.3 Insufficient Passing Opportunities

A potential inconsistency related to passing demand opportunities on a two-lane highway is simply that there are insufficient opportunities to pass given the traffic volumes and passing demand on the facility. This could be accomplished by conducting a full level-of-service (LOS) analysis of the roadway using the procedures of the *Highway Capacity Manual* (HCM) (*14*) and determining whether the design LOS selected by the user can be satisfied for the peak hour of the design year. However, this approach would require the relatively complex HCM procedures to be programmed as part of the expert system.

A simpler rule can be implemented based on a procedure developed in Canada. In this procedure, the percentage of net passing opportunities for one direction of travel on a two-lane highway is estimated as (*20*, *21*):

$$NPO = (100 - 100\,APL)(APZe^{-0.0018626\,OFLOW}) + 100\,APL, \tag{13}$$

where

NPO = percentage of net passing opportunities
APZ = proportion of segment length with marked passing zones (not including areas with passing or climbing lanes in the study direction)
APL = proportion of segment length with passing or climbing lanes in study direction
OFLOW = opposing flow rate (veh/h) during peak-flow in the study direction

Specific rules for *insufficient passing opportunities* follow.

8.3.1 Level 2 Warning. If NPO is greater than or equal to 50%, the supply of passing opportunities on the highway should be considered sufficient. If NPO is less than 50%, the following message should be displayed for the user:

> *Supply of passing opportunities between Stations XXX + XX and YYY + YY may be insufficient. An LOS investigation using the HCM procedures for two-lane highways is recommended.*

The procedure described above should be applied for each direction of travel for every segment of the roadway between points of substantial change in traffic volume (typically major intersections).

8.4 Passing Lane Too Short

Passing lanes should not normally be shorter than 0.3 km [0.2 mi], not including the lane addition and lane drop tapers. Passing lanes shorter than that length often do not provide an opportunity for one delayed vehicle to pass a faster vehicle.

Specific rules for *passing lane too short* follow.

8.4.1 Level 2 Warning. Each passing lane on the proposed roadway should be reviewed. If its length is less than 0.3 km [0.2 mi], the following message to the user should be displayed (*20*):

> *Passing lane for YY traffic between Stations XXX + XX and YYY + YY may be too short to provide even one passing opportunity.*

Consideration should be given to lengthening or removing the passing lane.

Passing lanes should also be long enough to contribute effectively to efficient operations. The minimum thresholds of passing lane length for operational efficiency are as follows (*20*):

Range of flow rates (veh/h) in study direction	Desired minimum length, km (mi)
0–300	0.80 (0.50)
300–550	1.20 (0.75)
over 550	1.60 (1.00)

If the length of any passing lane exceeds 0.3 km [0.2 mi], but is less than the appropriate threshold value shown above, the following message to the user should be displayed:

Passing lane for YY traffic between Stations XXX + XX and YYY + YY may be too short to be operationally efficient. An LOS investigation using the HCM procedures for two-lane highways is recommended.

8.5 Passing Lane Too Long

Passing lanes provide the greatest number of passing maneuvers in the initial portion of the lane. The portion of the passing lane that is used efficiently for passing maneuvers increases as the traffic volume increases. If a passing lane becomes too long, it might be more operationally efficient to end the passing lane and provide another passing lane some distance downstream. The maximum thresholds of passing lane length for efficient operations are as follows (*20*):

Range of flow rates (veh/h) in study direction	Desired maximum length, km (mi)
0–150	0.95 (0.60)
150–300	1.20 (0.75)
300–550	1.60 (1.00)
over 550	3.20 (2.00)

Specific rules for *passing lane too long* follow.

8.5.1 Level 2 Warning. If the length of any passing lane exceeds the appropriate threshold value shown above, the following message to the user should be displayed:

Passing lane for YY traffic between Stations XXX + XX and YYY + YY may be too long to be operationally efficient. Consider limiting the length of this passing lane and providing another passing lane downstream. An LOS investigation using the HCM procedures for two-lane highways is recommended.

8.6 Passing or Climbing Lane Addition Channels Slow Vehicles into Left Lane

A passing or climbing lane works most efficiently if the geometrics of the lane addition encourage slower vehicles to enter the right lane. By contrast, if the geometrics encourage all vehicles, including slower vehicles, to enter the left lane, the drivers of slower vehicles may be reluctant to move to the right and, consequently, the drivers of faster vehicles may be unable to pass. This can result in little gain in operational efficiency from the passing or climbing lane and may encourage irrational driver behavior that could lead to accidents.

Specific rules for *passing or climbing lane addition channels slow vehicles into left lane* follow.

8.6.1 Level 2 Warning. It does not appear practical to develop a set of rules for automated review of geometric plans to assess driver behavior at the lane addition to a passing or climbing lane. Therefore, the recommended procedure is to ask the user, for each passing or climbing lane, whether the geometrics are such that

- Lane addition geometrics cause most vehicles to enter the right lane.
- Lane addition geometrics cause most vehicles to enter the left lane.
- Lane addition geometrics do not favor either lane.

If the user selects the second option, the following message should be displayed to the user:

Passing lane addition for YY traffic at Station XXX + XX has geometrics that encourage most drivers to enter the left lane. This may reduce the operational benefits derived from the passing lane. Consider changes in geometric design or pavement markings at the lane addition to encourage most drivers to enter the right lane.

If the user selects the third option, the following message should be displayed to the user:

Passing lane addition for __ traffic at Station XXX + XX has geometrics that encourage use of either the left or right lanes by drivers. This may encourage some slower drivers to enter the left lane and may reduce the operational benefits derived from the passing lane. Consider changes in geometric design or pavement markings at the lane addition to encourage most drivers to enter the right lane.

9. Rule for Assessing the Frequency of Decisions on Roadway Segments

A rule has been developed for decision frequency on roadway segments. The purpose of this rule is to call attention to relatively short roadway segments that contain geometric and traffic control features that require drivers to make multiple decisions. The following design or traffic control elements are considered:

- Intersection;
- Major driveway;
- Railroad-highway grade crossing;
- Beginning or end of a horizontal curve with radius less than 800 m [2,600 ft];
- Vertical curve with available SSD less than that given in the Green Book for a design speed equal to 20 km/h [10 mph] less than the roadway operating speed;
- School zone;
- Narrow bridge (curb-to-curb width less than the roadway approach, including paved shoulder);
- Change in posted speed limit;
- Lane addition;
- Lane drop;
- Lane width reduction by 0.6 m [2 ft] or more; and
- Shoulder width reduction by 1.2 m [4 ft] or more.

9.1 Frequency of Decisions on Roadway Segments

Specific rules for *frequency of decisions on roadway segments* follow.

9.1.1 Level 2 Warning. The following message will be provided to the designer for a segment of 450 m [1,500 ft] in length that contains four or more of the geometric design and traffic control elements described above:

> *The roadway segment from Station XX + XXX to YY + YYY contains more than four geometric design or traffic control elements that require driver decisions. Consideration should be given to spacing these decisions over a longer roadway length, if practical.*

DATA NEEDS FOR DESIGN CONSISTENCY RULES

The data needed to evaluate a roadway design using the developed design consistency rules largely consist of information readily available to the designer. In some cases, however, additional information may have to be obtained to evaluate older alignments. Traffic information such as the 85th percentile speed should be obtained through the use of field measurements (for existing alignments) or estimated through the use of speed models or comparisons with comparable roadways. The data needed for the various elements are as follows.

- Sight Distance Rules
  - Roadway alignment and centerline stationing
  - Station of beginning and end of school zones
  - Station and direction of travel of passing/climbing lane drops
  - Station of ends of narrow bridges
  - Lane width and stations of points of change
  - Shoulder width and stations of points of change
  - Stations of railroad-highway grade crossings
  - Actual or estimated 85th percentile operating speed
  - Stations for major driveways
  - Available sight distance
- Horizontal Alignment Rules
  - Speed predictions
  - Location of horizontal curves
  - Shoulder width on tangent and on horizontal curve
- Vertical Alignment Rules
  - Percent downgrade
  - Length of downgrade
  - Calculated average downgrade for a segment of roadway with several different downgrades
- Driveway Rules
  - Roadway alignment and centerline stationing
  - Lane width
  - Shoulder width
  - Driveway locations by station and side of road
- Passing Demands and Opportunities
  - Roadway alignment and centerline stationing
  - Stations and directions of travel for beginnings and ends of passing/climbing lanes
  - Lane width and stations of points of change
  - Shoulder width and locations of points of change
  - Passing sight distance values for portions of the roadway outside passing/climbing lanes
  - Percent no-passing zones on portions of the roadway outside passing/climbing lanes or stations of beginnings and ends on no-passing zones
  - Upgrade traffic flow rate
  - Upgrade truck flow rate
  - Weight-to-power ratio of typical truck to be used for analysis
- Cross Section
  - ADT (vpd) for design year
  - Width of lanes by section, including roadway stationing for width changes
  - Width of shoulders by section, including roadway stationing for width changes
  - 85th percentile speed
  - Lane drop transition zone beginning and ending stations
  - Beginning and ending of lane addition transition stations
  - Location of major driveways
- Decision Frequency
  - Roadway alignment and centerline stationing
  - Stations of at-grade intersections
  - Stations of major driveways
  - Stations and directions of travel for beginnings and ends of passing/climbing lanes
  - Stations of beginning and end of school zones

  - Stations of ends of narrow bridges
  - Stations of railroad-highway grade crossings
  - Lane width and stations of points of change
  - Shoulder width and locations of points of change
  - Stations of changes in posted speed limit
- Narrow Bridges
  - Bridge width
  - Approach lane width
  - Available sight distance
  - 85th percentile speed on the approach
  - ADT (vpd) of the design year
- Highway-Railroad Grade Crossings
  - Design vehicle
  - Railroad grade crossing location stations
  - Station of stop line at intersection
  - Station of stop line at highway-railroad grade crossing
  - Available sight distance from stop line at highway-railroad grade crossing
  - Intersection sight distance computed from appropriate AASHTO case (i.e., through, left, and right) for approach with stop condition (used for signal and stop sign control) or permitted turning movements for through approaches (used for stop-protected approaches) as appropriate for the approach leg having the highway-railroad grade crossing

CHAPTER **4**

CONCLUSIONS AND SUGGESTED RESEARCH

The major conclusions of the research are the rules developed. The rules cover the following specific areas:

- Cross section,
- Horizontal alignment,
- Vertical alignment,
- Railroad grade crossings,
- Narrow bridges,
- Driveways,
- Preview sight distance,
- Climbing and passing lanes, and
- Frequency of decisions.

Each of the proposed rules was presented in Chapter 3. A brief review of their applicability to multilane roadways is provided below. Finally, recommendations for changes to the AASHTO Green Book are provided.

EVALUATION OF APPLICABILITY AND TRANSFERABILITY TO MULTILANE ROADWAYS

A review of the design consistency rules was undertaken to provide an assessment of their applicability for multilane roadways. In this review, the rules' potential use and applicability for the assessment of rural multilane and controlled access roadways was examined.

Cross Section

The cross-section rules fall into two groups: changes in section width (lane and shoulder) and adding or dropping a lane with a major driveway present. Both rule groups are generally amenable for use on multilane roadways, although preparatory work will have to be accomplished for one group.

The c*hanging lane width* and *changing shoulder width* rules are both suitable for use on multilane roadways, although the supporting safety relationships have not been developed. Accident modification factors for lane and shoulder width are not currently available for use on multilane roadways (i.e., other than two-lane rural). If those relationships were developed from the literature or a research study, however, the rules could easily be implemented for those types of facilities.

The *lane drop with major driveway* and *major driveway and lane addition* rules could be implemented at this time on multilane roadways. Given the typical greater traffic volumes associated with multilane roadways, these rules could be very beneficial in enhancing safety on these facilities. Of course, they would not be suitable for controlled access facilities that do not have driveways present on the roadway.

Horizontal Alignment

The rule *tight horizontal curve with wide shoulder* is applicable in principle to multilane roadways, but the underlying speed prediction equations and safety relationships are based on research performed on two-lane rural roadways. To fully support the rule, research would have to be performed to examine speed relationships and safety relationships on those classes of roadway.

It is unlikely that many multilane roadways would exhibit the tight horizontal curvature and associated speed changes as seen on two-lane roadways. The general safety relationship associated with shoulder width is expected to be similar, although its magnitude is likely to differ somewhat.

The rule would have to be modified to be applicable to multilane roadways. The underlying models predicting speed and safety on two-lane roadways would have to be established through further research.

Vertical Alignment

The rule *steep downgrades* could readily be applied to multilane roadways. The likelihood of the warning level being reached is less, however, due to the generally higher design standards in use on multilane facilities.

Railroad Grade Crossings

The rule *railroad grade crossing with intersection nearby* could readily be applied to multilane roadways. Although railroad grade crossings are less common on multilane roadways than on two-lane roadways, they are present on many facilities. The most common design reaching a warning level might be expected to be at intersections with two-lane facilities, however.

Narrow Bridges

The rule *narrow bridges* is expected to be applicable to multilane roadways after evaluation of the effects of reductions in shoulder width on speeds and modification of the models provided in the present rule.

System

The rule *frequency of decisions on roadway segments* could readily be applied to multilane roadways. Some of the factors would be expected to be less common on these types of roadways (i.e., beginning or end of a horizontal curve with radius less than 800 m [2,600 ft]) but their inclusion would be expected to remain appropriate. Consideration should be given to including other elements encountered on multilane roadways (e.g., introduction of a median).

Climbing and Passing Lanes

The rules associated with climbing and passing lanes would probably not be appropriate for multilane roadways, because the introduction of additional lanes for these purposes is uncommon on multilane roadways (assuming multilane facilities).

Driveways

The rules regarding driveways would have to be modified to be applicable to multilane roadways. The rule *access points or frequency of driveways* depends on speed and safety relationships for two-lane highways and would not be appropriate for multilane roadways without further research.

The rule *minimum separation between driveways* could be retained for multilane roadways, although modifications might be needed because of the presence of additional lanes. The increased volumes typically present on these roadways would tend to make the rule more urgent.

The rule *offset opposing driveways* would be readily applicable for multilane non-divided facilities; the rule would not be applicable to divided highways.

Sight Distance

The rules regarding stopping sight distance and decision sight distance are readily applicable to multilane facilities. Some of the elements listed would be unlikely to be encountered on those facilities (e.g., passing/climbing lane drops) and others would probably have to be added (e.g., introduction of a median), but these changes would be minor modifications to the rule.

RECOMMENDED CHANGES TO AASHTO GREEN BOOK

Based on the findings of this research, several changes are recommended for the AASHTO Green Book. It is recommended that a definition be provided for design consistency and that the design review section be supplemented with regard to using design consistency methodologies.

[insert following fifth paragraph, page 53]

Design Consistency

Design consistency is the conformance of a highway's geometric and operational features with driver expectancy. Measures that have been used to assess design consistency are changes in predicted 85th percentile speed, driver information handling, driver workload, changes in predicted roadway safety, and lane positioning.

Consistency with respect to these measures can help to ensure that roadway designs are developed that minimize the potential for driver error.

Design Assessment

[*insert following fifth paragraph, page 57*]

Roadway designs can be assessed for potential inconsistencies with regard to 85th percentile speed. FHWA has developed a tool that can be used to predict where large changes in 85th percentile speed may occur on rural two-lane roadways: the Interactive Highway Safety Design Model (IHSDM). This model allows the user to detect locations where the changes in 85th percentile speed may lead to safety concerns on the completed roadway.

Designers can also use design consistency rules for rural two-lane roadways developed in NCHRP 15-17 to determine where design inconsistencies related to changes in predicted safety, speed, and lane positioning may be found. Rules for detecting design inconsistencies related to cross section, horizontal and vertical alignment, driveways, railroad grade crossings, sight distance, narrow bridges, and decision frequency were developed in the study.

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APPENDIX A

LITERATURE REVIEW

FUNDAMENTAL ASPECTS OF CONSISTENCY AND EXPECTANCY

Consistency has a tremendous effect on learning and behavior. A frequent goal of training (whether intentional in classes or through responses learned in the "real" world) for tasks such as driving is the development of "automatic" behaviors, which can lead to improved performance (*1*). A review of the circumstances surrounding the development of automatic behavior is helpful in developing an understanding of the influence of consistency.

Significant psychology research has focused on learning and response, greatly clarifying the understanding of how individuals respond to stimuli under different response conditions. Using an example of a freeway exit and the outside edgeline, if a driver is attempting to stay in the lane and is monitoring the edgeline as an aide, the veering of the edgeline to follow an exiting roadway may be problematic in the area of the exit. The edgeline has shifted from being a "target" to being a "distracter." The practice of providing a dashed edgeline across exits partially ameliorates this effect.

Consistent Mapping Versus Variable Mapping

Consistent mapping (CM) occurs when target items are always targets and never function as distracters; variable mapping (VM) occurs when target items sometimes function as distracters (*2*). In work by Shiffrin and Schneider (*3*), comparisons of performance under the two test conditions revealed fundamental differences in responses. After sufficiently long periods of training, responses to VM conditions were greatly affected by load and were generally considered difficult. In contrast, responses to CM conditions were virtually unaffected by load and were easily accomplished. It appeared that serial search was used in the VM tests, while automatic detection was used in the CM tests.

In further testing using attention focused on certain target areas, Shiffrin and Schneider (*3*) found that stimuli used in CM training were difficult to ignore even when subjects were instructed to do so. The results indicated slowed responses because of the CM targets, even though they were irrelevant to the task under way.

Because training through encountering real-world situations does not always present consistency in its "targets," it is important to examine the validity of the concept of partially consistent training. That is, where targets are usually (rather than always) placed as targets, and similarly for distracters. Fisk and Schneider examined the effect of degrees of consistency in a series of studies (*2*). By varying the degree of consistency and then comparing performance, they concluded that "the higher the consistency during training, the better the performance in dual-task conditions." The benefits of practice were not found until several hundred trials had occurred. These results suggest that those benefits generally associated with automatic processing (including greater speed, parallel processing, less effortful performance, and nonresource consumptive) should occur in processes associated with a high degree of consistency, rather than only in those that are perfectly consistent. In further work, Fisk and Schneider found a similar response for consistent elements of an overall task that was not consistent (*2*).

One consideration in consistency is whether that consistency is localized in a specific set of stimuli or whether the consistency is contained by the relationships between stimuli (*4*). That is, if relationships across stimuli remain constant, improvements in performance due to consistent mapping can still be observed.

Another element of driving lies in the task being undertaken. Multiple tasks are frequently undertaken simultaneously. The driver turns on the turn signal, scans for conflicting traffic, accelerates around another vehicle, and completes the turning movement. In a study that reviewed performance in dual-task situations, Fisk and Lloyd found that the effects of consistency were even more exaggerated (*5*). By reducing the task through automatization of subtasks, performance was enhanced.

Review of these studies makes clear that consistency in learning and responding to stimuli in consistent manners is greatly enhanced. The degree of enhancement depends heavily on the degree of consistency present in the learning and operating environment. In elements such as intersections, where visual search and sometimes complex actions are critical to safely operating a vehicle, it is important that consistently mapped responses be learned and then designs complementing those learned responses used.

Because the development of automatic responses takes hundreds of repetitions, it should be understood that the final training of drivers largely takes place on the roadway network as they drive. The degree of consistency within that roadway network can either lend itself to the development of automatic, appropriate behaviors or it can lead to more error-prone operation through inconsistent designs.

DESIGN SPEED APPROACH TO ROADWAY DESIGN

One of the unifying elements of roadway design is the concept of "design speed." Design speed is used to determine the characteristics of various elements of the roadway. By using a single characteristic to determine the values of various criteria affecting the design elements of the roadway, the roadway's basic elements could theoretically be made consistent with the needs of the motorist.

Barnett's 1936 definition of design speed was "the maximum reasonably uniform speed which would be adopted by the faster driving group of vehicle operators, once clear of urban areas" (*6*). The design speed concept assumes that curves meet or exceed the criteria for the selected design speed. Originally, the design speed concept had two fundamental principles:

- All curves along an alignment should be designed for the same speed.
- Design speed should reflect the uniform speed at which a high percentage of drivers desire to operate.

As applied in the United States, the design speed concept presumes that a design will be consistent if the individual alignment features share the same or similar design speeds. Increasing concern with both fundamental principles has developed because of the differences in curve design along a route and the increase in operating speeds that are in excess of the design speed. These two issues conflict with the fundamental basis for the design speed concept.

Another concern with the design speed approach is that the values used to determine the geometry are minimum values for the given factor of safety, but AASHTO recommends using higher values whenever "such improvements can be provided as a part of an economical design" (*7*). Thus, different features may have different design minimums. This inconsistency in the design philosophy may violate drivers' expectancies of the roadway. Drivers may presume a safe operating speed based on previous alignment features, which may be higher than the design speed for the roadway, resulting in large speed fluctuations. Leisch and Leisch concluded that the design speed concept did not guarantee consistency in highway alignment because of the variation in operating speed for roadways with design speed less than 90 km/h [56 mph] (*8*). The Green Book does note:

> Isolated features designed for higher speeds would not necessarily encourage drivers to speed up, although a succession of such features might. In such cases, the entire section of highway should be designed for a higher speed. A substantial length of tangent between sections of curved alignment is also likely to encourage high-speed operation. In such situations, a higher design speed should be selected for all geometric features, particularly sight distance on crest vertical curves and across the inside of horizontal curves. (*7*)

One of McLean's criticisms of the design speed concept is that design speed has been used as a means of designing horizontal and vertical curves and that design speed has "no real meaning with regard to long tangent segments" (*9*). Krammes and Glascock support McLean's criticism and cite the tangent as one of the limitations of the design speed concept: "The design speed applies only to horizontal and vertical curves, not to the tangents that connect those curves" (*10*). Consistency concerns develop when long tangents allow drivers to achieve their desired speeds but the resulting speed is in excess of the design speed of the following curve.

Leisch and Leisch cite several concerns with the design speed philosophy, but acknowledge the widespread use of the concept (*8*). They developed a consistency check to be incorporated in the design speed procedure to represent "the potential operating speed that is determined by the design and correlation of the physical features of a highway." In the purest form, they recommend that a maximum design speed change of 15 km/h [9.3 mph] between features. Features that do not meet the criteria are considered to be inconsistent. Further considerations are given to the differences in speeds between passenger vehicles and trucks, but these recommendations are based on operating speeds, rather than the design speed.

Factors used to select design speed are functional classification, rural versus urban, and terrain (as designated by AASHTO); AASHTO Green Book procedure, legal speed limit, legal speed limit plus a value (e.g., 8.1 to 16.2 km/h [5 or 10 mph]), anticipated volume, anticipated operating speed, development, costs, and consistency (state DOTs); and anticipated operating speed and feedback loop (international practices). Functional classification is used by the majority of the states, with legal speed limit being used by almost one-half of the states responding to a mailout survey (*11*). A concern with the use of legal speed limit is that it does not reflect a large proportion of the drivers. Only between 23 and 64% of drivers operate at or below the posted speed limit on non-freeway facilities. The legal speed limit plus 16.1 km/h [10 mph] included at least 86% of suburban/urban drivers on non-freeway facilities with speed limits of 40.2 to 88.5 km/h [25 to 55 mph] and included at least 96% of rural drivers on non-freeway facilities with speed limits of 80.5 to 112.7 km/h [50 to 70 mph] (*11*).

ELEMENTS OF ROADWAY DESIGN

Several factors influence the design of roadways, including design speed, sight distance, horizontal and vertical alignment elements, cross section features, and intersection design. Design speed was discussed in the previous section. Following are discussions on key geometric features and how they may relate to design consistency.

Sight Distance

Sight distance,"the length of roadway ahead visible to the driver" (*7*), allows drivers to adjust vehicle controls in order to make safe movements so as to avoid possible obstructions. Sight distance should be determined during field visits, because vegetation, signs, disabled vehicles, or other obstacles may interfere with available sight distance. Little practical research has been done to relate sight distance to design consistency, even though sight distance is a key element in geometric design.

Horizontal Curvature

Challenges arise when developing design consistency practices for the definition of inconsistent horizontal curves. From the perspective of individual roadway, if an entire roadway is in mountainous terrain, then drivers should expect small radius horizontal curves and a reduction in speed should correspond to the topography. In this scenario, a large radius horizontal curve may be considered inconsistent because it has a design speed in excess of the other horizontal curves. This horizontal curve may give drivers a false sense of security while approaching the next horizontal curve. All things being equal, a road with similar horizontal curve radii would be expected to have a lower crash rate per mile than a road with large fluctuations in the curve radii.

Historically, the most critical geometric design element that influences driver behavior and poses the most potential for crashes has been the horizontal curve (*12,13*). Previous research on rural two-lane highway operations and safety has concluded that horizontal curves whose design speed is less than drivers' desired speed exhibit operating speed inconsistencies that increase crash potential (*12*). Several factors are associated with the increased frequency of crashes on horizontal curves: restricted sight distance, driver inattentiveness, speed estimation errors, and centerline crossover are typical examples of how drivers may react inappropriately to the change in alignment. Horizontal curves have a high likelihood of inconsistency due to the varying design procedures and the complexity of control and guidance throughout the horizontal curve.

Crash rates are typically 1.5 to 4 times higher on horizontal curves than on the tangent segments (*13*). The familiar design formula is used to determine the acceptable radius for the given conditions, but several research projects have shown that speeds on horizontal curves may exceed the design speed if the design speed of a two-lane rural highway curve is less than 90 km/h (*11*). This finding suggests that the design speed concept, in its current form, does not fully address driver perception of smaller radius curves. In general, small radius curves violate drivers' a priori expectancies. Additionally if a small radius curve is situated among larger, more forgiving, radius curves, the curve will violate the ad hoc driver expectancy.

Side friction is specified for driver safety and/or comfort. Side friction exceeding limits will increase the steering effort to avoid lane violations, resulting in uncomfortable driving situations and a possible reduction in speed. McLean states that side friction is fundamental to curve design, but that the "design values must be based on a realistic assessment of driver behavior and comfort tolerance of modern drivers" (*9*). Thus, the design speed concept as it applies to superelevation and side friction has generally been found acceptable for design speeds in excess of 100 km/h [62 mph], but for curves with a design speed less than 100 km/h [62 mph], driver behavior is "completely at variance with the assumption underlying the design speed approach."

Superelevation is a geometric feature used to reduce side friction demand by counterbalancing a portion of the centripetal acceleration encountered by drivers. AASHTO design procedures assume that the sum of side friction and superelevation equals centripetal acceleration. The current design speed approach allows for different maximum superelevation rates on similar radius curves. Krammes and Garnham discussed the different maximum superelevation standards throughout the United States (*14*). The range of maximum rates resulted from different climates, but even these differences can result in a similar design with vastly different design speeds.

Taragin found that "superelevation as normally used in terms of feet per foot of pavement width without regard to the sharpness of the curve bears no relation to the percentage of vehicles exceeding the safe speed based on curvature and superelevation," but there is a close correlation between the "superelevation per foot of degree of curvature and the percentage of vehicles exceeding the computed safe (design) speed based on curvature and superelevation" (*15*). Kanellaidis suggested that "the use of design speed to determine individual geometric elements like superelevation rates should be reevaluated and replaced by operating-speed parameters" (*16*).

Horizontal Alignment Consistency

The objective in providing desirable horizontal alignment is to provide elements that are consistent with what drivers expect based on their experience on similar roadways and on previous sections of a particular roadway. Large differences and abrupt changes in horizontal alignment should be avoided so that driver workload is not excessive. Significant changes in driver workload requirements often lead to crashes. For safety reasons, the horizontal alignment must be consistent in terms of sight distances. This will also preserve the design speed of the roadway. Independent design of these features tends to increase crash potential. Consistency of these features can be determined from the plan-profile sheets of the design.

Vertical Alignment

Vertical alignment design is a derivative of the interaction between sight distance criteria, the topography of the roadway, and the designer's need to meet ancillary goals (e.g., balancing excavation and fill quantities). Vertical curves are designed to provide smooth transitions between tangent gradients. The ideal design of these features provides adequate sight distance to allow for stopping once a driver has detected an object in the travel lane. Unfortunately, the terrain does not always allow for economical provision of safe and recommended sight distances. These limited sight distance curves by themselves generally do not violate the driver's expectancy of the roadway. When these features are followed by a sharp horizontal curve or an intersection that may require speed reduction, driver expectancy is violated and the pair of features could be deemed inconsistent.

Coordination of Horizontal and Vertical Alignment

Horizontal and vertical alignment should complement each other and be considered in combination. Topography and right-of-way are usually the controlling features affecting the coordination of horizontal and vertical alignment. Sight distances computed from horizontal and vertical curves would be desirable so as to have a safe roadway and to reduce the driver workload. Thus, the combination of design elements must meet the minimum requirements of either the horizontal or vertical design element, whichever controls the sight distance.

The interaction of horizontal and vertical alignment is the least studied aspect of geometric design because of the complexity of the geometry. Generally, horizontal and vertical alignments are designed separately to meet certain criteria and then brought together, assuming that design consistency will be maintained. This assumption is not always valid, which AASHTO discusses in a very brief section on ensuring consistent combined design. The discussion focuses on avoiding certain key combinations of horizontal and vertical alignment (i.e., sharp horizontal curve following a crest vertical curve) and maintaining certain aesthetic guidelines, but gives little design guidance to quantify acceptable consistency.

Cross Section and Right-of-Way

The design of the cross section of a roadway may also pose decision problems to the driver. Research has shown that small clear zone and roadway widths have a tendency toward higher crash rates. The clear zone is the total roadside border area, starting at the edge of the traveled way, available for use by errant vehicles. This area may consist of a paved or unpaved shoulder, a recoverable slope, a non-recoverable slope, and/or a clear run-out area.

Travel lane width and condition of the surface greatly affects the safety and comfort of driving. Two-lane rural highways can show undesirable conditions such as inadequate vehicle clearances and edge-of-pavement clearances when narrow lanes are present. The addition of shoulders or improved shoulder widths and the removal of roadside hazards can reduce the severity and frequency of crashes associated with run-off-the-road situations (*13*). These crashes typically occur because of (1) overload of the workload necessary to perform the control task or (2) driver inattentiveness. The sudden change in roadway cross section and surroundings often causes a sudden increase in the operating task required of the driver. These sudden changes can include lane drops, narrow bridges, and reduced shoulder width. Properly designed roadsides with no encroachments complement the roadway design by providing adequate sight distance to improve operations, reduce the number of potential roadside hazards to increase safety, and integrate the roadway within the surrounding landscape to provide a positive visual and psychological reference for the driver.

Intersection Design

The design of intersections depends on the interaction of various elements. These elements must be coordinated if the intersection is to operate safely and efficiently. Issues that must be considered include human factors, traffic, physical constraints, and economics.

The angle at which the two intersecting roadways cross greatly affects the safe operation of the intersection. Intersections with large or small crossing angles increase the conflict area, limit visibility, increase the turning area for large vehicles, and increase the time of exposure in the intersection for crossing vehicles (*17*). Enhancements to the intersection may be necessary to mitigate the effects of the skew angle. These enhancements can include improved traffic control through the placement of traffic signals or stop signs or increased paved area to accommodate truck maneuvers.

The accommodation of intersections near horizontal curves presents special problems for the roadway designer. Intersecting roadways that depart in line with the tangent prior to a horizontal curve violate aspects of design consistency. Drivers must turn their vehicles to follow the main roadway even though a roadway continues straight ahead. In addition, many perceptual cues that would guide the driver along the main roadway are missing or misleading in this case. Edgelines frequently are discontinued in the intersection area or follow the exiting roadway, and fence lines may follow the exiting roadway before rejoining the main roadway on the far side of the intersection or horizontal curve, thus leading to perceptual problems that create false impressions about the roadway environment.

CONSISTENCY METHODOLOGIES

Several design consistency methodologies have been proposed for use. These methodologies frequently center on the application of one measure of effectiveness (MOE) and seek to limit the variability of that MOE. By limiting the variability of that one key MOE, a "consistent" roadway is thus provided. The selection of an appropriate MOE is critical to the success of such a strategy. MOEs that have been used include speed (through speed prediction), driver workload (or visual demand), speed variance, and alignment indices.

Speed is an easily measured, highly variable quantity that appears to be closely related to the driver's perception of the roadway and the immediate environment. Reactions to changes in that perception appear to be quickly reflected in changes in the speed selected by the driver. Limiting required changes in speeds to acceptable limits appears to provide the basis for an improvement in the operation of the roadway because required driver actions can be limited, reducing the potential for inappropriately selected speeds.

Driver workload is also a measure that has been used in the measurement of design consistency. By limiting the workload imposed on the driver to acceptable levels, the likelihood of overloading the driver's mental capacity is reduced. Providing a consistent level of workload could increase the likelihood of desirable operating characteristics being observed. An MOE closely related to workload is visual demand. Visual demand is considered to be a surrogate for driver workload because driving is essentially visual in nature. By measuring the amount of incoming information to the driver (the amount of "vision" needed), a measure of the workload imposed on the driver can be obtained.

Statistical measures of sample speed populations are considered an alternative form of design consistency that can be used to identify potential problems of individual features on specific roadways. Alignment features exhibiting higher values of speed variability have been identified as potential locations for driver error. Significant changes in speed distributions may suggest that design inconsistencies are present at that alignment feature.

Alignment indices may hold some promise for design practice in the United States; however, the different design characteristics and use of these indices must be considered when attempting to apply the alignment indices in the United States. For example, German road design uses a more curvilinear alignment than the United States, and the English use their indices to predict a space-mean speed over extended sections of the roadway, not a spot speed. Germany also does not predict spot speeds, as their index predicts 85th percentile speeds of roadway sections with similar alignment characteristics.

CONSISTENCY METHODS BASED ON SPEED PREDICTION

Speed profile models predict operating speeds along a roadway and determine speed differences between successive features. These models can be used to visually check operating speeds between tangent segments and horizontal curves along the roadway. Horizontal curves may restrict the desired speed of drivers. Thus, to safely and comfortably traverse sharper curves, drivers must decelerate on entering the horizontal curve. The speed-profile model then assumes that operating speeds remain constant throughout the curve. Acceleration occurs on exiting the horizontal curve, and prediction of tangent operating speeds is based on assumed deceleration and acceleration rates for the length and grade of the tangent segment. Knowledge of these components allows for the graphical representation of operating speeds and speed differences between features.

Several studies have investigated the relationships between the various speed elements. Some of the studies have tried to predict operating speed using roadway characteristics. Following are the summaries of the relationships identified in the literature.

Rural Two-Lane Highways

1999 FHWA Study

In a late 1990s FHWA research project, several different efforts were undertaken to predict operating speed for different conditions on two-lane rural highways, such as on horizontal and vertical curves, on tangent sections, and prior to or after a horizontal curve *(18)*. Speed data were collected at more than 200 two-lane rural highway sites for use in the project. Table A-1 lists the developed speed prediction equations. Following is a summary of the findings for different alignment conditions.

Horizontal Curves on Grades. Four different vertical grade conditions were considered in the evaluation of horizontal curves on grades: upgrades (0 to 4%), steep upgrades (greater than 4%), downgrades (–4 to 0%), and steep downgrades (less than –4%). Figure A-1 shows that as R increases from 0 to 400 m [0 to 1,312.3 ft], the 85th percentile speeds increase notably for all study locations. For radii greater than 400 m [1,312.3 ft], the increase in speed is not as dramatic. The inverse of the radius was the variable most highly correlated to the 85th percentile speed of all the variables included within the correlation matrix (see Figure A-2). The regression model developed to fit the data for horizontal curves on grades included the single independent variable, $1/R$.

Three of the four speed prediction equations have intercept values greater than the 97.9 km/h recommended by Krammes et al. on "long" tangents (*12*). Long tangents were defined as tangents where drivers can reach their desired speed for the roadway. Therefore, in certain situations, the equations would predict speeds higher than the assumed speed on a long tangent. Observed speeds on long tangents ranged from 93 to 104 km/h [57.8 to 64.6 mph] (average 85th percentile speed, by state). Based on the data and engineering judgment, the maximum operating speed on horizontal curves and tangents could be rounded to 100 km/h [62.1 mph]. Thus, operating speeds on large radius horizontal curves should be truncated to 100 km/h [62.1 mph] (or to another desired operating speed) when the predicted speed exceeds this value.

Vertical Curves on Horizontal Tangents. Vertical curves on horizontal tangents were divided into three categories: nonlimited sight distance (NLSD) crest curves, limited sight distance (LSD) crest curves, and sag curves. Data for the ver-

TABLE A-1 Speed prediction equations for passenger vehicles (*18*)

AC EQ (See note 1)	Alignment Condition	Equation (see note 2)	Num. Obser.	R^2	*MSE*
1.	Horizontal Curve on Grade: -9% ≤ G < -4%	$V_{85} = 102.10 - \frac{3077.13}{R}$	21	0.58	51.95
2.	Horizontal Curve on Grade: -4% ≤ G < 0%	$V_{85} = 105.98 - \frac{3709.90}{R}$	25	0.76	28.46
3.	Horizontal Curve on Grade: 0% ≤ G < 4%	$V_{85} = 104.82 - \frac{3574.51}{R}$	25	0.76	24.34
4.	Horizontal Curve on Grade: 4% ≤ G < 9%	$V_{85} = 96.61 - \frac{2752.19}{R}$	23	0.53	52.54
5.	Horizontal Curve Combined with Sag Vertical Curve	$V_{85} = 105.32 - \frac{3438.19}{R}$	25	0.92	10.47
6.	Horizontal Curve Combined with Non-Limited Sight Distance Crest Vertical Curve	(see note 3)	13	n/a	n/a
7.	Horizontal Curve Combined with Limited Sight Distance Crest Vertical Curve (i.e., K ≤ 43 m/%)	$V_{85} = 103.24 - \frac{3576.51}{R}$ (see note 4)	22	0.74	20.06
8.	Sag Vertical Curve on Horizontal Tangent	V_{85} = *assumed desired speed*	7	n/a	n/a
9.	Vertical Crest Curve with Non-Limited Sight Distance (i.e., K > 43 m/%) on Horizontal Tangent	V_{85} = *assumed desired speed*	6	n/a	n/a
10.	Vertical Crest Curve with Limited Sight Distance (i.e., K ≤ 43 m/%) on Horizontal Tangent	$V_{85} = 105.08 - \frac{149.69}{K}$	9	0.60	31.10

NOTES:
1. AC EQ = Alignment Condition Equation Number
2. Where: V_{85} = 85th percentile speed of passenger cars (km/h); R = radius of curvature (m); K = rate of vertical curvature; G = grade (%)
3. Use lowest speed of the speeds predicted from AC EQ 1 or 2 (for the downgrade) and AC EQ 3 or 4 (for the upgrade).
4. In addition, check the speeds predicted from AC EQ 1 or 2 (for the downgrade) and AC EQ 3 or 4 (for the upgrade) and use the lowest speed. This will ensure that the speed predicted along the combined curve will not be better than if just the horizontal curve was present (i.e., that the inclusion of a limited sight distance crest vertical curve results in a higher speed).
5. n/a = not applicable
6. *MSE* = mean square error
7. 1 km/h = 0.62 mph

tical curves on tangents were collected at a total of 21 study sights: two for NLSD crest curves, ten for LSD crest curves, and nine for sag curves. The independent variables considered included *K* and 1/*K* (see Figures A-3 and A-4, respectively).

Of the independent variables, 1/*K* was most highly correlated to the 85th percentile speeds, even though the correlation was low for some conditions. The relationship between 85th percentile speed and 1/*K* is shown in Figure A-4. Also included on these figures are the data from the NCHRP Stopping Sight Distance (SSD) study (*19*) and the plot of the selected regression equation for the limited sight distance condition.

No statistically significant regression equation was found for NLSD curves on horizontal tangents; therefore, the desired speed for long tangents is assumed for this condition. This recommendation is based on the graphical representation of the four sites and engineering judgment.

A total of nine sag curves on horizontal tangents sites were available for the analysis. As with the crest curves, the scatter plot does not show a clear relationship between the variables (see Figure A-4). Therefore, based on the plots and attempts at developing a regression equation, it was recommended that the desired speed on long tangents be used for this alignment condition. Extreme sag vertical curves where the *K*-value is less than 15 may result in reduced operating speeds; however, the available data are too sparse to make a definitive conclusion on the issue.

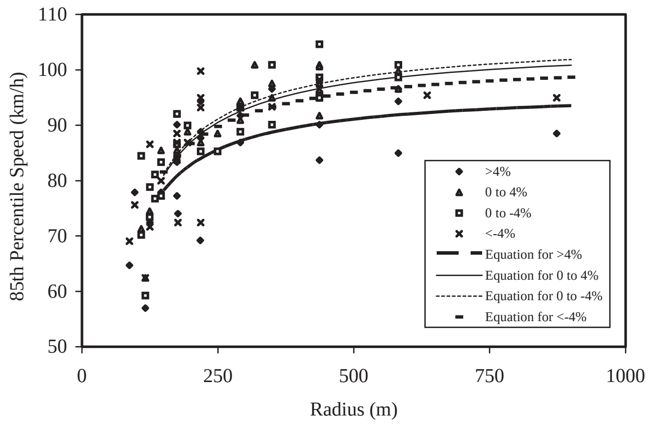

Figure A-1. Horizontal curves on grades: V_{85} versus R (18).

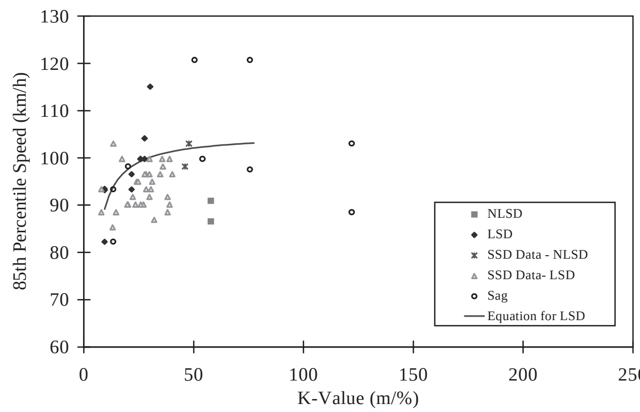

Figure A-3. Vertical curves on horizontal tangents: V_{85} versus K (18).

Combination of Horizontal and Vertical Curves. The analysis of the combination curves (i.e., sites with both a horizontal curve and a vertical curve) began with plotting the speed data versus *R*, 1/*R*, *K*, and 1/*K*. Plots for *R* and *K* are shown in Figures A-5 and A-6, respectively. Initial evaluation of the plots indicated that both *R* and *K* could influence the speed along the combination of curves.

A statistically significant regression equation was not found for non-limited sight distance crest vertical curves in combination with horizontal curves. One of the reasons was that the data used in the analyses were for curves with larger radii. Drivers on a combination of large horizontal radii and non-limited sight distance crest curves may not feel the need to reduce speed in response to the geometry. The inclusion of all available data from this study also did not identify a regression equation with significant variables. All tested models that used variations of *R* and *K* had both insignificant variables and very low R^2 values. Therefore, engineering judgment must be used to determine the predicted speed for a horizontal curve combined with a non-limited sight distance crest vertical curve. Based on a review of the data available for this condition and for similar conditions, the lowest speed predicted using the equation developed for the following conditions is recommended:

- Assumed maximum desired speed on long tangents,
- Predicted speed using the horizontal curve radius equation for the upgrade, and
- Predicted speed using the horizontal curve radius equation for the downgrade.

Using the lowest predicted speed will ensure that the speed predicted along the combined vertical and horizontal curve will not be better than if just the horizontal curve was present.

Limited sight distance crest curves combined with horizontal curves were evaluated using the 22 study sites available. Regression analysis compared the influences of 1/*K*, 1/*R*, and an interaction term. The analysis demonstrated that only 1/*R* was significant in predicting 85th percentile speeds.

The equation developed for the combination of sag vertical curves and horizontal curves included data from the 25

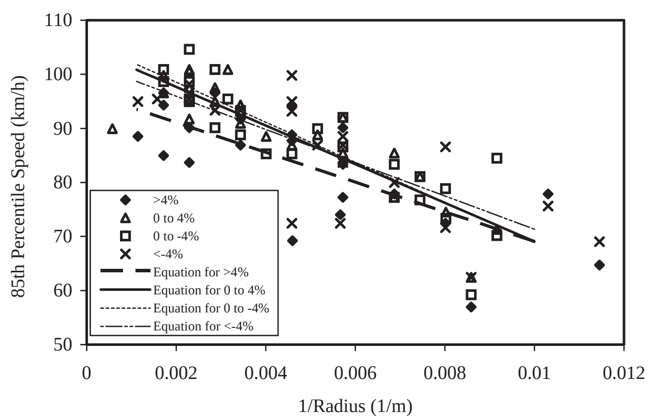

Figure A-2. Horizontal curves on grades: V_{85} versus 1/R (18).

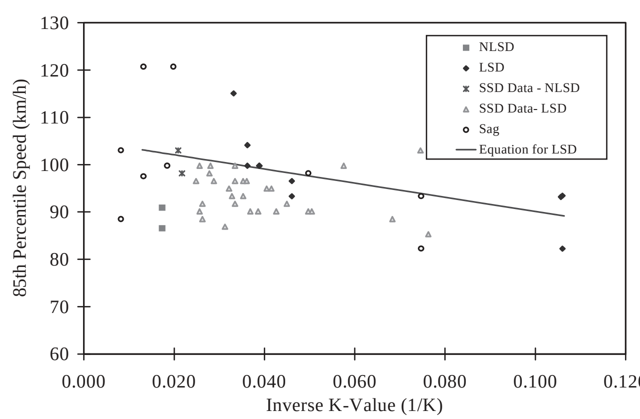

Figure A-4. Vertical curves on horizontal tangents: V_{85} versus 1/K (18).

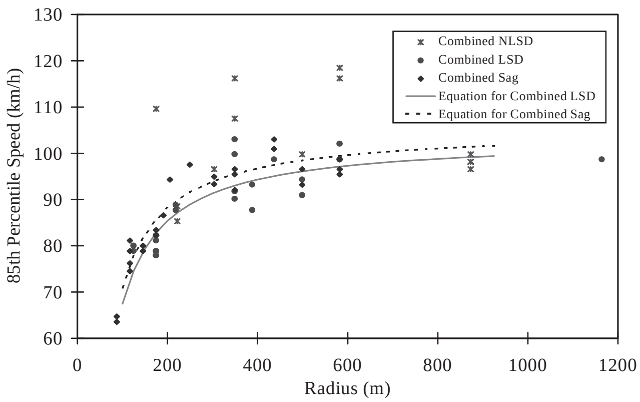

Figure A-5. Combination curves: V_{85} versus R (18).

sites. It revealed that 1/*R* was the only significant independent variable.

Tangents. The estimation of speeds on curves is easier than the prediction of speeds on tangent sections because of the strong correlation of speeds on a few defined and limiting variables, such as curvature, superelevation, and the side-friction coefficients between road surface and tires. On tangent sections, however, the speed of vehicles depends on a wide array of roadway characteristics (e.g., the length of the tangent section, the radius of the curve prior to and after the section, cross-section elements, vertical alignment, general terrain, and available sight distance). Few studies have dealt with this issue to date because a considerable database is necessary to identify any significant trends, and a substantial modeling effort is required. An attempt was made using operating speeds on 162 tangent sections of two-lane rural highways (*20*). The work developed models for speed prediction based on the geometric characteristics available. Initially, a one-model approach was used; however, because of the low R^2 value, a family of models was developed that better predicted operating speeds.

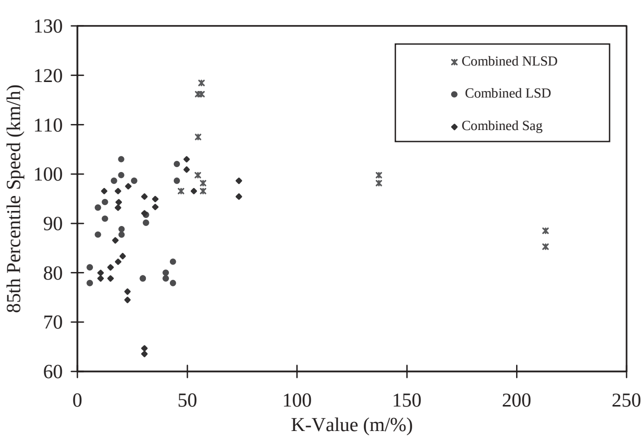

Figure A-6. Combination curves: V_{85} versus K (18).

The analyses showed that when determining 85th percentile speeds in the middle of a tangent section, it is necessary to observe a longer section—one that includes the preceding and succeeding curves—because these constitute the primary variables affecting speed. The influence of secondary geometric variables was investigated and found not to affect speed as much as the primary variables. Several geometric measures characterizing the geometry of the entire section (the tangent and attached curves) were developed, and the best measure was adopted for the development of the prediction models.

After considerable examination of the 162 sites, it was decided to assemble the data into four groups of similar characteristics. Separate prediction models for the 85th percentile speed were developed for each of the four groups and are listed in Table A-2. The models for sections in Groups 1 and 2 provided a good fit to the data and could be adapted for prediction purposes during the planning process for new two-lane highways. The models for sections in Groups 3 and 4 were preliminary and need additional data. Further research was also suggested on the effect of some secondary variables, such as the cross-section elements (lane width and roadside characteristics) and the longitudinal slope on the 85th percentile speed on two-lane rural highways.

Other Rural Two-Lane Highway Studies

Lamm et al. studied 260 curves in New York and developed a model based on the degree of curvature to determine 85th percentile operating speeds (*21*). The model originated from his previous work on German guidelines for prediction of operating speeds. The German approach used curvature change rate (CCR) as the independent variable in the regression equation to estimate the operating speed. Lamm et al. found no major differences between using degree of curvature or CCR, but they recommend the degree of curvature for use on most U.S. two-lane rural roads because of its common use in design.

Their model to quantify design consistency separates highway designs into three categories (*21*):

1. Good Design: Change in degree of curvature less than or equal to 5 deg, or a change in operating speed less than or equal to 10 km/h [6.2 mph];
2. Fair Design: Change in degree of curvature greater than 5 deg and less than or equal to 10 deg, or a change in operating speed greater than 10 km/h [6.2 mph] and less than or equal to 20 km/h [12.4 mph]; and
3. Poor Design: Change in degree of curvature greater than 10 deg, or change in operating speed greater than 20 km/h [12.4 mph].

A good design is considered consistent. Fair designs have some minor inconsistencies that may affect the driver's behavior. Poor designs have inconsistencies that cause predicted speed differentials exceeding 20 km/h [12.4 mph] (*21*).

TABLE A-2 Models to predict speeds on two-lane rural highway tangent sections (*20*)

Group	Description	Model	R^2
1	Small radii (≤250 m [819.7 ft]) Small tangent lengths (< 150 m [491.8 ft])	$SP = 101.11 - 3420/GM_s$ $GM_s = (R_1 + R_2)/2$	0.553
2	Small radii (≤250 m [819.7 ft]) Intermediate tangent length (150 to 1000 m [491.8 to 3278.7 ft])	$SP = 105.00 - 28.107/e^{(0.00108 \times GM_L)}$ $GM_L = [TL + (R_1 + R_2)^2]/100$	0.742
3	Intermediate radii (> 250 m [819.7 ft]) Intermediate tangent length (150 to 1000 m [491.8 to 3278.7 ft]) GM_L (1500 to 7500)	$SP = 97.73 + 0.00067\ GM_L$ $GM_L = [TL + (R_1 + R_2)^2]/100$	0.200
4	Large tangent length (> 1000 m [3278.7 ft]) "reasonable" radii (i.e., does not violate the minimum-radius criterion for assumed design speed of road)	$SP = 105.00 - 22.953/e^{(0.00012 \text{ X } GML)}$ $GM_L = [TL \text{ x } (R_1 + R_2)^2]/100$ (Note: only based on 6 points; considered a preliminary model)	0.838

Where: SP = 85th Percentile Speed (km/h),
GM_s = geometric measure of tangent section and attached curves for short tangent lengths (m),
R_1 = Upstream radius (m),
R_2 = Downstream radius (m),
GM_L = geometric measure of tangent section and attached curves for long tangent lengths (m), and
TL = Tangent length (m).

1 km/h = 0.62 mph

Based on the previous work conducted by Lamm and Choueiri, Choueiri et al. conducted research on 25 curved roadway sections. Their results developed guidelines for consistency of changes in operating speed and design speed criteria. The following categorizes three different design criteria (*22*):

- **Good Designs:** The change in the degree of curve is ≤5 deg and the change in operating speed V_{85} is less than or equal to 10 km/h [6.2 mph] between successive design elements. Design Speed Criterion: The difference between the operating speed and the design speed is less than or equal to10 km/h [6.2 mph] for the investigated curve or tangent. For these road sections, consistency in horizontal alignment exists and no improvements in geometric design would be necessary. No adaptations or corrections between design speed and operating speed have to be conducted.
- **Fair Designs:** The change in the degree of curve is $5 < DC \leq 10$ deg and the change in operating speed 10 km/h $< V_{85} \leq$ 20 km/h [6.2 mph $< V_{85} \leq$ 12.4 mph] between successive design elements. Design Speed Criterion: The difference between the operating speed and the design speed is 10 km/h $< V_{85} - Vd \leq$ 20 km/h [6.2 mph $< V_{85} - V_D \leq$ 12.4 mph] for the investigated curve or tangent. These road sections exhibit minor inconsistencies in geometric design. Normally, correcting the existing alignment may be avoided by using low-cost warning devices. Superelevation rates in curves should be related to the expected 85th percentile operating speeds with respect to the degree of curve and not to the design speed.
- **Poor Designs:** The change in the degree of curve is >10 deg and the change in operating speed $V_{85} >$ 20 km/h [12.4 mph] between successive design elements. Design Speed Criterion: The difference between the operating speed and the design speed is >20 km/h [12.4 mph] for the investigated curve or tangent. These road sections represent strong inconsistencies in the horizontal geometric design that may result in critical driving maneuvers. Crash rates will be higher for these road sections. The 85th percentile operating speed should not be allowed to exceed the design speed by more than 20 km/h [12.4 mph]. If such a difference occurs, an increase in the design speed is recommended.

In a 1991 *Public Roads* article on advisory speed-setting criteria, Chowdhury et al. (*23*) reported on speed data for 28 horizontal curves in three states (Maryland, Virginia, and West Virginia). They measured the 85th percentile speed and determined the corresponding horizontal curve design speed. The inferred design speed was computed using the standard superelevation equation given the degree of curvature and measured superelevation rate near the midpoint of the curve and assuming that the maximum coefficient of side friction recommended by AASHTO was not exceeded. All of the curves with a design speed of 81 km/h [50.3 mph] or less had 85th percentile speeds that exceeded the design speed. Only on the single 97 km/h [60.3 mph] design speed curve was the observed 85th percentile speed less than the design speed.

In a previous FHWA study, speed data were collected at 138 horizontal curves on 29 rural two-lane highways in five states (New York, Oregon, Pennsylvania, Texas, and Washington) in three geographic regions (*12*). Inferred design speed was determined from the standard superelevation equation given the degree of curvature and measured superelevation rate near the midpoint of the curve and assuming that the AASHTO maximum coefficient of side friction was not exceeded. The data, shown in Figure A-7, indicate that the 85th percentile speed exceeded the inferred design speed on all but two curves with design speeds of 80 km/h [49.7 mph] or less. In contrast, the 85th percentile speed was less than the inferred design speed for all curves with design speeds of 110 km/h [68.4 mph] or more. For the curves with 100 km/h [62.1 mph] design speeds, an almost equal number had 85th percentile speeds greater than and less than the inferred design speed. The disparity between the 85th percentile speeds and inferred design speeds is greatest for the lowest design speeds. The data in these studies clearly show that the radius of the horizontal curve affects operating speed.

The recent NCHRP study on stopping sight distance measured operating speed on limited sight distance crest vertical curves (*19*). Figure A-8 shows the measured speeds versus inferred design speed. The plot indicates that as the inferred design speed increases (i.e., greater available sight distance), operating speeds are higher. The reduction in speed between a control location and a crest vertical curve was also determined in the study. The data indicated that available sight distance appears to influence mean speed reductions. Specifically, the mean reductions in speed between the control and crest sec-

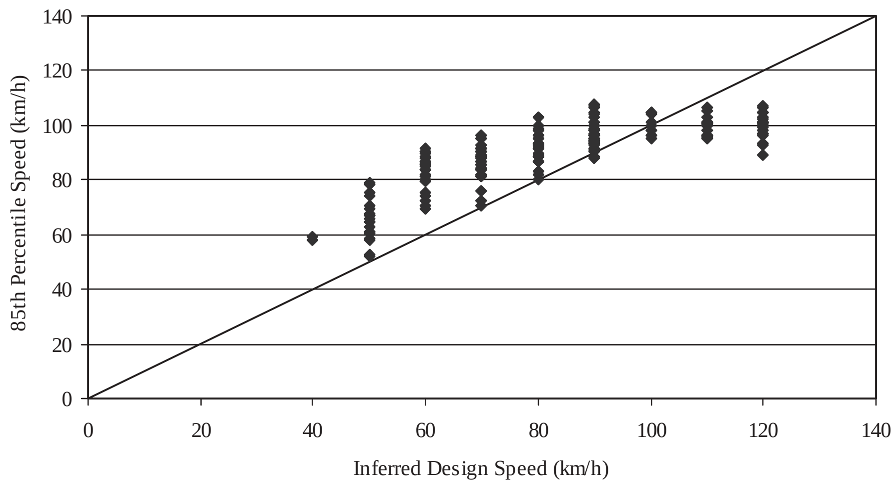

Figure A-7. 85th Percentile speed versus inferred design speed for 138 rural horizontal curves (12).

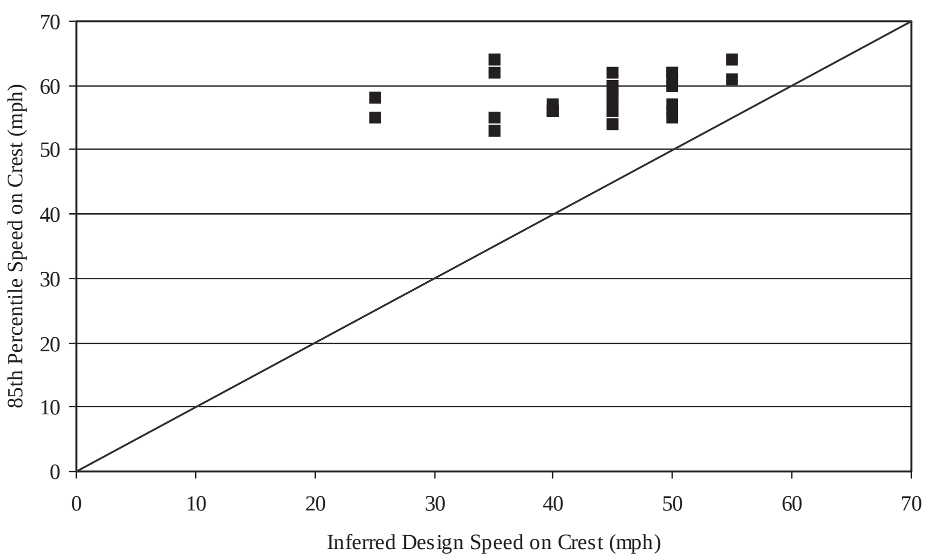

Figure A-8. 85th Percentile speed versus inferred design speed for limited sight distance crest vertical curves (19).

tions tend to increase as available sight distance decreases; however, the reduction in speed is less than that suggested by the current AASHTO criteria.

McLean *(24,25)* also found similar design speed/operating speed disparities on rural two-lane highways in Australia. McLean found that horizontal curves with design speeds less than 90 km/h [55.9 mph] had 85th percentile speeds that were consistently faster than the design speed, whereas curves with design speeds greater than 90 km/h [55.9 mph] had 85th percentile speeds that were consistently slower than the design speed. McLean's findings prompted a revision of the Australian design procedures for roadways with lower design speeds.

Schurr et al. (*26*) developed regression equations for horizontal curves on rural two-lane highways in Nebraska. Posted speeds ranged from 88.6 to 104.7 km/h [55 to 65 mph] for the sites used in the analysis. The regression model developed for the 85th percentile speed resulted in the approach grade, deflection angle, and curve length being the significant independent variables (see Table A-3). The authors noted that the design speed used to develop the horizontal curve elements of the roadway alignment should match the observed 95th percentile vehicular speeds. Figure A-9 shows the observed 95th percentile speeds at the midpoint location versus the inferred design speed determined from the geometric elements of horizontal curves at each of the 40 sites. The inferred design

TABLE A-3 Regression equations for horizontal curves in Nebraska (*26*)

Location	Regression Equation	Num. Obser.	R^2	MSE
85^{th} Percentile Speed Midpoint of Horizontal Curve	$V_{85,\,mid} = 103.3 - 0.1253\,DA + 0.0238L - 1.038G_1$	50	0.46	14.13
85^{th} Percentile Speed Approach	$V_{85,\,app} = 70.2 + 0.434Vp - 0.001307T_{ADT}$	50	0.19	23.04

where:
$V_{85,\,mid}$ = 85^{th} percentile speed at free-flow passenger cars at the curve midpoint (km/h).
DA = deflection angle (decimal degrees).
L = arc length of curve (m).
G_1 = approach grade (percent).
$V_{85,\,app}$ = 85^{th} percentile speed of free-flow passenger cars at the approach location (km/h).
Vp = posted speed (km/h).
T_{ADT} = average daily traffic (vehicles per day).
1 km/h = 0.62 mph.

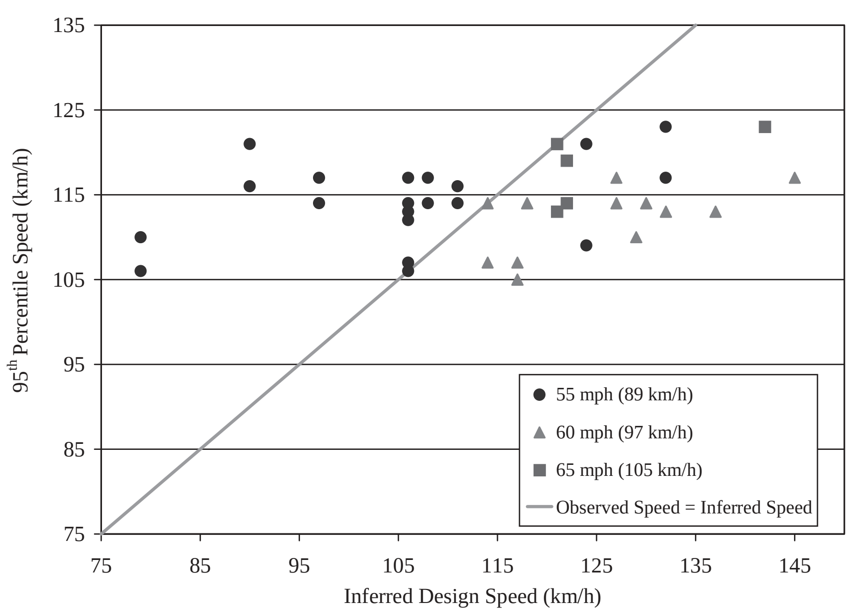

Figure A-9. Observed 95th percentile speed versus inferred 95th percentile speed based on 2001 Green Book model at the midpoint location (26).

speed was determined using the 2001 AASHTO model. For 17 of the 40 sites, the 95th percentile operating speed was greater than the inferred design speed. All these sites were in the 55-mph posted speed category. The authors commented that there appears to be no direct relationship between 95th percentile operating speed and inferred design speed. This finding supports the view of some researchers that some drivers determine their desired speed based on what they perceive to be reasonable for certain roadways types (such as rural two-lane highways).

Jessen et al. (*27*) collected speed data on 70 crest vertical curves in Nebraska. Multiple linear regressions were used to determine the crest vertical curve, roadway, traffic, and speed characteristics that affect speeds on crest vertical curvature. The posted speed of the highway was found to have the most influence on the operating speed. The inferred design speed of the vertical curves was not a significant factor.

A recent project completed in Europe was reported by Cardoso et al. (*28*). In this study, 50 curves in four countries were studied for their effects on speed. Unimpeded speeds were examined using several different variables:

- Curve radius,
- Curve length,
- Lane width,
- Shoulder width, and
- Longitudinal gradient.

Of those variables, the only significant terms were curve radius and the 85th percentile speed on the preceding tangent. Models were developed for each of the countries included in the data collection effort (France, Portugal, Greece, and Finland). Table A-4 lists the equations. A similar form was obtained for three of the countries, resulting in equations containing the reciprocal of $R^{1/2}$; the equation for the remaining country (France) used the reciprocal of R^2. A common model for the complete database was developed using the reciprocal of $R^{1/2}$, although it was decided that the models developed for the individual countries were superior. The models developed were as follows.

In addition to the 50 curve sites, 80 tangents were also studied. Characteristics representing the 500 m preceding the speed measurement section of the tangent included the following:

- Average bendiness,
- Average lane width,
- Average shoulder width,
- Total upgrade,
- Total downgrade,
- Average gradient, and
- Total hilliness.

Because all variables were not available in each country, a common equation was not developed. Equations developed to estimate speeds on tangents are listed in Table A-5.

TABLE A-4 Regression equations for unimpeded speeds on curves in Europe (*28*)

Country	Regression Equation	Num. Obser.	R^2	MSE
France	$S85 = 49\ 220 \quad \frac{292736}{R^2} + 0\ 454 \times S85_{AT}$	28	0.80	4.02
Finland	$S85 = 51.765 \quad \frac{337.780}{\sqrt{R}} + 0.6049 \times S85_{AT}$	5	0.71	5.92
Greece	$S85 = 41.363 \quad \frac{294.000}{\sqrt{R}} + 0.699 \times S85_{AT}$	9	0.92	5.91
Portugal	$S85 = 25.010 \quad \frac{271.500}{\sqrt{R}} + 0.877 \times S85_{AT}$	35	0.90	6.1
Complete database	$S85 = 35.086 \quad \frac{289.999}{\sqrt{R}} + 0.759 \times S85_{AT} + c$	77	0.87	5.8

Where:
S85 = 85th percentile of the unimpeded speed distribution (km/h).
R = curve radius.
$S85_{AT}$ = 85th percentile of the unimpeded speed on the tangent immediately preceding the curve section (km/h).
c = constant used to adjust the Y intercept for each country, with
c = 0.000 Finland; *c* = -3.665 France
c = -0.033 Greece; *c* = 2.107 Portugal
1 km/h = 0.62 mph.

TABLE A-5 Regression equations for unimpeded speeds on tangents in Europe (*28*)

Country	Regression Equation	Num. Obser.	R^2	MSE
France	$S85 = 97.737 + 0.007436\,L - 45.707 Bend$	28	0.65	5.4
Finland	$S85 = -17.17 + 0.02657L + 33.711LW - 21.936SW$	5	0.768	5.6
Greece	$S85 = 134.069 - 3.799Hill - 126.59Bend$	9	0.92	6.12
Portugal	$S85 = -29.95 - 34.835LW - 0.0347PRad - 43.124Bend$	34	0.82	7.58

Where:
*S*85 = 85^{th} percentile of the unimpeded speed distribution (km/h).
L = Tangent length (m).
Bend = Bendiness (degree/km).
LW = Lane width (m).
Hill = Hilliness (percent).
PRad = Radius of the curve preceding the tangent section (m).
1 km/h = 0.62 mph.

Summary of Speed Prediction Models

Several studies have investigated the relationship to operating speed of design speed and various roadway characteristics on rural two-lane highways. Horizontal curvature is the most researched design element related to operating speed. As evidenced by the vast number of studies available on the topic, a definite relationship exists between operating speed and horizontal curvature. In general, as the radius of the curve decreases or the degree of the curve increases, the operating speed decreases. Several models have been developed to predict the operating speed on a rural two-lane highway horizontal curve. Table A-6 summarizes a sample of these models that predict speed at the midpoint of a horizontal curve. Table A-7 summarizes the findings from the research on operating speed relationships on tangent sections of rural two-lane highways.

Equations have also been developed for vertical curvature and for combined horizontal and vertical alignment on rural two-lane highways, although not to the extent that equations have been developed for only horizontal curvature.

TABLE A-6 Variables influencing midpoint horizontal curve operating speed for rural two-lane highways (*11*)

Author (year)	Influencing Roadway or Roadside Variable						R^2
	Degree of Curve	Radius	Length of Curve	Deflection Angle	Inferred Speed	Grade	
Tarigan (1954)	X						74
Dept of Main Roads, New South Wales (1969)		X					83
Emmerson (1969)		X					na
McLean (1979)		X			X		92
Glennon (1983)	X						84
Lamm (1988)	X						79
Krammes et al. (1993)	X		X	X			82
Islam et al. (1994)	X						98
Fitzpatrick et al. (1999)		X				X	53-76
Schurr et al. (2002)			X	X		X	46

TABLE A-7 Variables influencing operating speed on tangent for rural two-lane highways (*11*)

Author (year)	Influencing Roadway or Roadside Variable					R^2
	Preceding & succeeding curves	Access Density	Tangent Length	Region of Country	Grade	
Parma (1999)		NF		X	X	NP
Polus et al. (2000)	X	NF	X			23-55

* NP = not provided.
NF = study design limited range for this variable.
X = found to be statistically significant or correlated with operating speed.

CONSISTENCY METHODS BASED ON DRIVER WORKLOAD

Workload Definition

Workload has been defined by Senders (*29*) as "a measure of the 'effort' expended by a human operator while performing a task, independently of the performance of the task itself." Another definition of workload was given by Knowles (*30*) as consisting of the answer to two questions: "How much attention is required?" and "How well will the operator be able to perform additional tasks?" The definition presented by Knowles is very appropriate to the driving environment, given that it consists of many overlapping tasks, each requiring a portion of the driver's attention. A method of examining the workload demands placed on the driver would appear to be a way of directly arriving at the capabilities of the driver as he or she negotiates a given roadway. Kanellaidis states that design consistency is indirectly associated with how drivers maneuver geometric features, while driver workload is directly related to it (*31*).

Messer defines driver workload as "the time rate at which drivers must perform a given amount of work or driving tasks" (*32*). He indicates that driver workload increases with reductions in sight distance and increasing complexity of geometric features. Glascock concluded that "combinations of features increase workload and may be more hazardous to drivers than successive features with adequate separation" (*33*). Thus, a horizontal curve combined with a vertical curve may increase the driver workload associated with guidance and control by (1) having alignment features that, in combination, reduced sight distance (guidance) and (2) requiring more complex vehicle maneuvering (control). If the combination of horizontal and vertical features includes an unexpected or extreme feature, the workload is increased even more. Consequently, as the complexity of the geometric feature increases, the higher the workload and the greater the probability of a significant speed change.

Workload as a Measure of Design Consistency

In Messer and Messer et al.'s studies of roadway design and its effect on driver performance, considerable attention has been given to the concept of mental workload as an approach to measuring or rating the design (*32*, *34*). The driver is more or less continuously processing visual and kinesthetic information, making decisions, and carrying out control movements.

Generally, little visual information processing capacity is required of the experienced driver to perform the driving task. It is performed almost at a subconscious level as long as the roadway is free of traffic and obstacles and as long as the driver's visual evaluations are consistent with the tracking requirements. Consistency of the visual evaluation of the roadway with the actual roadway requirements is a function of the sight distance and the driver's expectancies regarding the roadway. A consistent roadway geometry allows a driver to accurately predict the correct path while devoting little visual information processing capacity, thus allowing attention or capacity to be dedicated to obstacle avoidance and navigation.

The studies reported by Messer and Messer et al. (*32*, *34*) presented a method of evaluating driver workload. By gathering empirical evidence regarding driver expectations of roadway features and relating violations of those expectancies to workload, a model was formed. The model is based on the presumption that the roadway itself provides most of the information that the driver uses to control the vehicle; hence, the roadway imposes a workload on the driver. This workload is higher during encounters with complex geometric features and can be dramatically higher when drivers are surprised by encounters with combinations or sequences of severe geometric features (see Figure A-10).

The driver workload procedure quantifies design consistency by computing a value for driver workload. The technique relies on a set of assigned ratings developed for various roadway elements. Roadway features receiving ratings are (in order of severity) bridges, divided highway transitions, lane

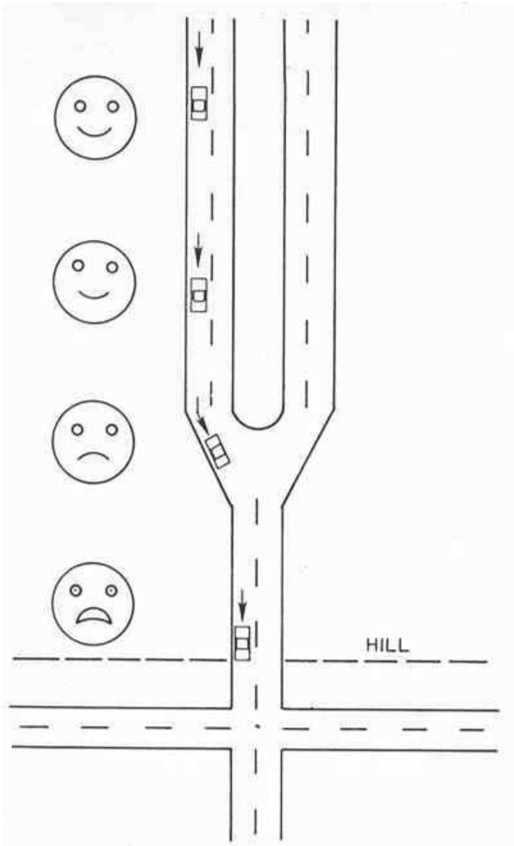

Figure A-10. Example of compound geometric inconsistency (32).

drops, intersections, railroad grade crossings, shoulder-width changes, alignment, lane-width reductions, and the presence of crossroad overpasses. The ratings, based on the type and severity of design element, are then modified in accordance with their location. Influencing factors include sight distance to the element, similarity to previous elements, workload of previous segments, and percentage of drivers estimated to be familiar users of the facility. The workload along the roadway is estimated using an equation which defines a subjective Level of Consistency (LOC) in terms related to driver workload (*32*). The results from the design consistency procedure are reported in a range extending from A, “no problem expected,” to F, “big problem possible.”

Although two recent studies (*10, 35*) have indicated generally acceptable results when relating crash rates and the workload values derived using Messer et al.’s procedure, problems have arisen when attempting to use the procedure in locations with closely spaced features. Workload carry-over effects may be overstated in those cases, although conclusive evidence has not been published.

In a 1990 study directed primarily at studying motorcycle safety, Hancock, Wulf, Thom, and Fassnacht (*36*) found increased mental workload during turn sequences when compared with straight driving. Workload was measured through the use of response time to the illumination of a probe light; subjective workload judgments were also measured through use of the National Aeronautics and Space Administration (NASA) *Task Load Index* procedure and the United States Air Force *Subjective Workload Assessment Technique.* No significant difference in workload for left and right turns was found, although the consequences of failing to detect an oncoming vehicle were noted to be quite different for the two maneuvers.

Vision Occlusion

Using an approach initially reported by Senders et al. (*37*), Krammes et al. (*12*) examined design consistency for horizontal curves using vision occlusion to study driver workload. Vision occlusion was used to determine the effective workload on the driver. Drivers wore an occlusion device that provided fixed-length glimpses of the roadway in response to presses of a switch. Recording the frequency and location of requested glimpses provided a measure of the amount of information needed to traverse the roadway successfully. They found that workload increased linearly as the degree of curvature increased, increasing on the approach to and peaking near the beginning of horizontal curves. No effect was found for deflection angle.

Extending the work begun by Krammes et al. (*12*), a late 1990s FHWA research study explored the use of vision occlusion to evaluate design consistency (*38*). Like the previous study, a test-track study was used to examine driver workload; however, companion efforts were also performed using on-road and simulator studies. Curve sequence, separation distance between curves, radius, and deflection angle were examined through the use of vision occlusion and subjective ratings. Vision occlusion is a technique that measures driver visual demand on a roadway. When testing, the driver could request a glimpse of the road for a set interval of time by pressing a floor-mounted button with his or her left foot. Drivers were instructed to request only as much vision as necessary to stay on the course. Subjective ratings using a modified Cooper-Harper scale were also collected from the participants. Efforts to include heart-rate variability as a measure of driver workload were discontinued after collecting initial data and thoroughly exploring the suitability of its use in a short-term, transient task such as traversing a highway curve.

The study found that visual demand was closely related to radius. Visual demand was defined as the percentage of time that the driver is actively looking at the roadway and was measured by use of a vision occlusion visor that blocked the driver’s vision when vision had not been requested by the driver by the use of a floor-mounted switch.

Relationships between visual demand and the inverse of radius were determined for various conditions, including test track, on-road, and simulator studies in the analysis (*39*). Although the overall level of visual demand was different for each study type, similar results were found when the slopes were compared (see Figure A-11). That is, when differences in workloads were compared between various radii, similar findings resulted. The exception to that similarity occurred when visual demand over the complete curve was compared between the test track and simulator studies. The trends were generally similar, however, and comparisons over the first 30 m [98 ft] of the curves resulted in a finding of no significant difference (see Figure A-12). Because the 30 m [98 ft] comparison was judged more critical than the complete curve, generally satisfactory comparisons were found. The general trend of the "workload" on the curves as reflected by the visual demand values was confirmed by the findings from the use of the Cooper-Harper modified scale. Drivers were asked to estimate the difficulty of driving the horizontal curves using the scale (1–10 subjective difficulty scale); the small radius curves were found to be judged more difficult to drive.

Additional work undertaken in the late 1990s FHWA study included comparisons between curves preceded with varying tangent lengths and with curve pairs with differing curve orientation (i.e., widely separated S-curves, widely separated broken-back curves, closely separated S-curves, and closely separated broken-back curves). Although statistically significant results were obtained, the findings were somewhat difficult to interpret with only small overall differences in visual demand.

CONSISTENCY METHODS BASED ON SPEED VARIANCE

Analysis of potential relationships between speed variability and geometry may identify inconsistent locations. Currently, design speed policy does not consider speed variations within and between design elements.

The purpose of a late 1990s research study was to identify the relationship between rural two-lane highway geometry and speed variability (*38*). Locations with geometric features exhibiting higher values of speed variability may be locations associated with driver error. Significant changes in speed distribution measures may also suggest that design inconsistencies are present between alignment features. One basis for using descriptive speed statistics originates from the idea that speed variance—not speed magnitude—is the issue (*40*).

Drivers have a desired operating speed—the speed at which they would operate if unimpeded by other traffic. Assuming that desired speeds are related to free-flow speeds, desired speeds can be approximated using a sample of free-flow vehicle speeds. The similarities between desired and free-flow speeds suggest that free-flow speeds depend on drivers' perceptions of the roadway conditions, environment, and geometry. Thus, free-flow speeds and the statistical measures associated with them may identify alignment deficien-

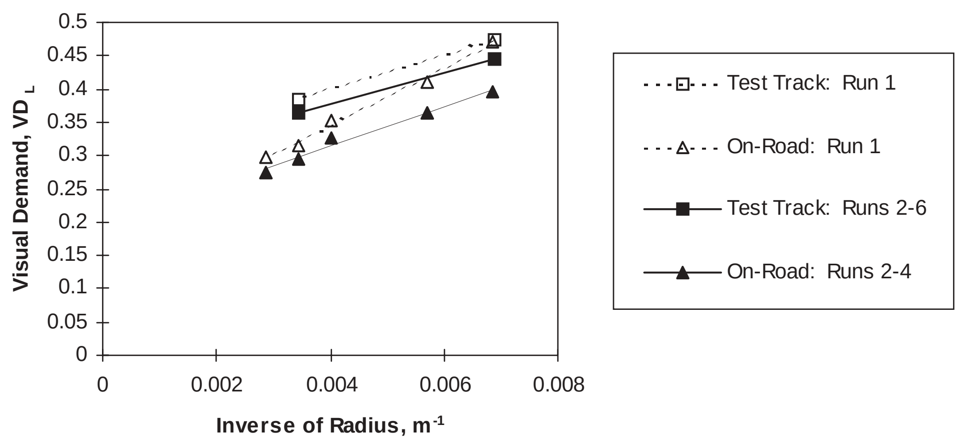

Figure A-11. VD_L versus inverse of radius (39).

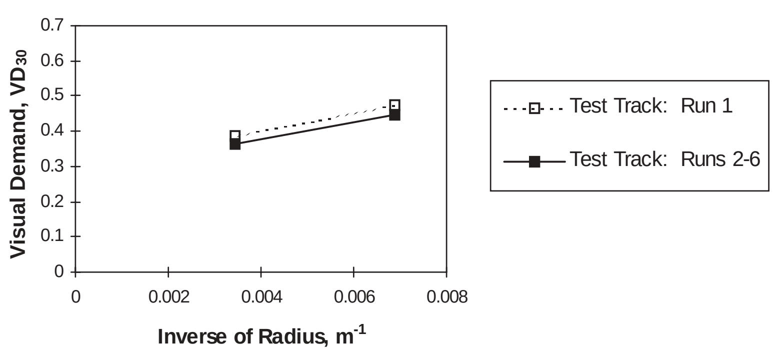

Figure A-12. VD_{30} versus inverse of radius (39).

cies. A common hypothesis in traffic flow theory is that speeds, particularly of free-flowing vehicles, are normally distributed. Continuous distributions have interval scales with certain properties defined in terms of actual units of measurement (*41*). It is believed that vehicle speeds on roadways follow a continuous distribution and that distribution measures could identify geometric deficiencies.

The hypotheses that would enable speed variance measures to be used to evaluate geometric design consistency do not appear to be valid. In general, there was low correlation between geometric features and speed variance. Large differences in speed variance existed for the different design and posted speeds. As expected, there was a relationship between speed distribution measures of successive features, but this relationship resulted from sampling the same drivers. Speed standard deviation does appear to change between horizontal curves and tangents, but the change is in the direction of the lower, rather than the higher, speed variance on horizontal curves than on tangents. This finding makes the use of speed variance inappropriate in identifying design inconsistencies.

These results indicate that speed variance is not an appropriate measure of design consistency for horizontal curves on rural two-lane highways. Although an increase in speed variance may be an indicator of potential safety problems for some geometric design features or traffic situations, it is not useful in explaining safety differences between tangents and horizontal curves on two-lane highways.

CONSISTENCY METHODS BASED ON ALIGNMENT INDICES

Alignment indices are quantitative measures of the general character of a roadway segment's alignment. Average radius per roadway section, average vertical curve, curvature change rate per kilometer, and others are examples of alignment index measures that have been developed to define the general characteristics of a roadway section. Table A-8 lists a sample of alignment indices. In theory, roadway sections with significant changes in horizontal or vertical alignment have alignment index values requiring more driver information processing to perform the driving task.

Speed and geometry data from a sample of rural two-lane highway sections in six states were used to determine whether alignment indices are statistically significant predictors of tangent speeds (*38,42*). The findings of a 1990s FHWA research project indicated that, although a few reasonable models were developed, alignment indices by themselves and combinations of alignment indices and other geometric variables were not statistically significant predictors of 85th percentile speeds on long tangents of rural two-lane highways (*38,42*).

DESIGN CONSISTENCY METHODS IN OTHER COUNTRIES

Design consistency is widely used in other countries. The Australian guidelines include "a consistency check that the

TABLE A-8 Alignment indices selected for evaluation (*38*)

Horizontal Alinement Indices	Vertical Alinement Indices
• Curvature Change Rate - CCR (degrees/km) $\frac{\sum \Delta_i}{L}$ where: Δ = deflection angle (degrees) L = length of section (km)	• Vertical CCR - V CCR (degrees/km) $\frac{\sum A_i}{L}$ where: A = absolute difference in grades (degrees) L = length of section (km)
• Degree of Curvature - DC (degrees/km) $\frac{\sum DC_i}{L}$ where: DC = degree of curvature (degrees) L = length of section (km)	• Average Rate of Vertical Curvature - V AVG K (meters/percent) $\frac{\sum \frac{L}{\lvert A \rvert}}{n}$ where: L = length of vertical curve (km) A = algebraic difference in grades (%) n = number of vertical curves
• Curve Length: Roadway Length - CL:RL $\frac{\sum (CL)_i}{L}$ where: CL = curve length (m) L = length of section (m)	• Average Gradient - V AVG G (meters/km) $\frac{\sum \lvert \Delta E_i \rvert}{L}$ where: ΔE = change in elevation between VPI_{i-1} and VPI_i (meters) L = length of section (km)
• Average Radius - AVG R (meters) $\frac{\sum R_i}{n}$ where: R = radius of curve (meters) n = number of curves within section	**Composite Alinement Indices** • Combination CCR - COMBO (degrees/km) where: $\frac{\sum \Delta_i}{L} + \frac{\sum A_i}{L}$ Δ = deflection angle (degrees) A = absolute difference in grades (degrees) L = length of section (km)
• Average Tangent - AVG T (meters) $\frac{\sum (TL)_i}{n}$ where: TL = tangent length (meters) n = number of tangents within section	

design speeds of successive elements should differ by no more than 10 km/h" (*43*). French researchers have found that "a consistency check is important and that safety problems are associated with sharp horizontal curves that are preceded by long tangents" (*44*). The French policy specifies "a minimum radius following long tangent segments."

Babkov suggests a classification technique for analyzing isolated curves following long tangents (*45*). His procedure compares the change in operating speeds between the tangent and the horizontal curve. The recommendations are as follows:

- "Safe curves" exist when the change in speeds is less than 20%;
- "Relatively safe curves" exist when the change in speeds is between 20 and 40%;
- "Dangerous curves" exist when the change in speeds is between 40 and 60%; and
- "Very dangerous curves" exist when the change in speeds is greater than 60%.

Several countries have developed speed profile models and consider them in the design process. Switzerland initially developed speed profile models based on curve radius. Germany uses a rating of the roadways curvature to predict speed. Following is a summary of how consistency is considered in Australia, Britain, and Germany.

Australia

The Australian design guide for rural roads incorporates a procedure for evaluating speed consistency (*43*). McLean performed much of the research that led to this procedure (*46*). McLean was also the first to define desired speed in the way it is used in this paper: "the speed at which drivers choose to travel under free-flow conditions when they are not constrained by alignment features." McLean suggested that desired speed was influenced by such factors as the purpose of the trip, proximity to urban areas, and the amount of time that traffic was on the road; he also suggested that desired speed was influenced by the geometric characteristics, or the overall standard of alignment, of the roadway. The Australian design guide provides a table of standard values for the speed environment of a roadway (i.e., desired speed), based on McLean's work, for different terrain types (e.g., flat, undulating, hilly, mountainous) and ranges of horizontal curve radii (*43*).

Britain

British designers incorporate the horizontal and vertical components of a roadway section into one overall alignment value. British design practice describes the concepts as the "bendiness and hilliness" of a roadway (*47*). The design speed is based on a trial alignment. Alignment indices are used to determine actual "journey" speeds based on predetermined models that are compared with the design speed for the roadway section. This iterative approach requires detailed geometric information prior to the final completion of the design. British standards call for a journey speed over a roadway section that is defined based on the homogeneity of roadway sections with a minimum section defined as no less than 2 km. Average curve characteristics, average visibility, the number of access points per kilometer, road type, and shoulder width are generally the variables used to predict the journey speed over the section. The journey speed is calculated and then compared with the trial design speed for the section.

The layout constraint measures the degree of constraint imparted by various characteristics of the roadway and is determined based on the following roadway conditions (*47*):

- Road type,
- Travelway width,
- Degree of access and junction, and
- Shoulder width.

Unfortunately, the journey speed approach does not consider the microscopic inconsistencies associated with transition points between features. Thus, although the journey speed model may predict a speed that is consistent with the design speed, a long tangent or large radius curve followed by a small radius curve may enter into the design without producing a journey speed less than the design speed.

Germany

In determining the design consistency of their roads, German designers use a parameter for the horizontal alignment called the curvature change rate (CCR). The CCR is the sum of angular changes in the horizontal alignment divided by the length of the highway section. This parameter is used in an attempt to prevent unsafe changes in operating speeds and to describe the overall operating characteristics of a road (*48*). German designers take other parameters into consideration in checking the consistency of roadway design. These parameters include the lengths of circular curves, transition curves, and tangents as well as the radii of all circular curves. In addition, nomographs in the German design manual are used to provide guidance on safe combinations of successive curves.

There are mixed views on the applicability of the CCR method for possible use in the United States. Some researchers argue that the CCR method is most convenient for predicting changes in operating-speed profile along a rural roadway brought about by inconsistencies in the horizontal alignment—compared with a graphical speed-profile technique proposed for use in the United States and a theoretical speed model used by the Swiss highway design community (*22*). Lamm, Hayward, and Cargin suggest that the CCR method would be "convenient to use in the process of locating inconsistencies in horizontal alignment and that it can be easily adapted to the American design system"; however, they also think that "because the German method assumes similarities of road characteristics within a given road section, this procedure may be difficult to introduce into overall American design practices" (*49*).

The CCR method has other disadvantages as well. While roads in Germany are designed with few tangents and many curves, U.S. designs use simple circular curves with long tangents to allow for passing and overtaking maneuvers. The curvilinear alignment used in Germany allows for an easy determination of sections of roadway with similar alignments; however, it was difficult in determining sections with similar alignments in applying the CCR procedure to a sample of roads in the United States. A final disadvantage is that Germany relies on the subjective selection of segments that are "homogeneous" when computing the CCR.

The research of Lamm et al. showed that in the case of curvilinear alignment, which is common practice in Germany, the CCR method may be more advantageous to use than the Degree of Curvature method.

SUMMARY OF LITERATURE REVIEW

The methods for evaluating and guaranteeing design consistency on rural highways can be divided into those based on design speed and those based on operating speed. In the United States, AASHTO's design-speed approach is the standard; however, it has some problems that may not guarantee the desired consistency in all situations. International practice and U.S. research confirm that methods based on operating speeds should also be used to ensure design consistency. These methods are even more important in low design-speed rural highways where the operating speeds are higher than the design speeds.

The 85th percentile of a sample of speeds measured at a specific location is generally accepted as a measure of the operating speeds on that location. Therefore, the ability to predict the 85th percentile speed using geometric variables is critical to the operating speed-based methods. Research and foreign practice have identified horizontal radius as the main variable when estimating speeds on horizontal curves on rural two-lane highways. Passenger car speeds on vertical curves are mainly affected by rate of vertical curvature. Trucks and recreational vehicles are affected by grade and the length and steepness of grade.

There are two main problems with existing approaches to design consistency. One is the inability to study combinations of horizontal and vertical alignments. Horizontal alignments combined with vertical alignments increase the driver workload and the potential for speed changes. Currently, the only alternative to check consistency on combined alignments is to look at a three-dimensional perspective of the alignment. This method is not quantitative and cannot measure the effect of the alignment on driver behavior. The other problem is that the speed prediction equations were developed for passenger cars only. Trucks and recreational vehicles may be affected differently than passenger cars by combinations of horizontal and vertical alignment.

Alignment indices have been developed in England and Germany where they are used as a tool in the design of the roadways. The alignment indices used in England and Germany help predict the 85th percentile operating speeds of motorists. In trying to estimate the 85th percentile operating speeds on long tangents, previous studies reviewed in this chapter used either the intercept of a linear regression equation for curves or the mean of the 85th percentile operating speeds as the estimated speed.

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APPENDIX B

GEOMETRIC DESIGN FEATURES THAT INFLUENCE DESIGN CONSISTENCY

Design consistency is a tool or measure used to evaluate or modify roadway designs for consistency with driver expectancy. Features should be considered from the viewpoint that they affect driver decision-making or ability. The potential for the inclusion of particular geometric features for use in a design consistency methodology is contingent on whether a feature affects driver response or behavior.

A survey was undertaken to review geometric design features that could influence design consistency. A total of 17 design engineers, consultants, law enforcement personnel, and accident reconstructionists were contacted and surveyed via telephone. The survey provided a view of those geometric features that the respondents considered most critical for design consistency. Features were rated on a scale of 1 to 10 (1 being least influential and 10 being most influential); a score of 0 was assigned when respondents did not believe the feature had an influence on design consistency.

The elements in the survey are listed in Table B-1. The 40 features (e.g., vertical curve and pavement cross-slope) or feature aspects (e.g., radius of horizontal curve and intersection skew angle) had an overall average rating of 3.7, although a relatively clear demarcation was present between features commonly indicated to have a high influence on design consistency and those thought to have a low influence on design consistency.

GEOMETRIC ELEMENTS SURVEY FORM

Design Consistency Background Information

Transportation safety research is needed to reduce the number and severity of accidents on roadways. Safety through proper roadway designs is essential to minimizing the decision-making process and driver uncertainties.

Currently, there is strong interest in evaluating roadway designs to ensure that features are consistent with drivers' expectations. Inconsistent features or combinations of features place a greater demand on the driver, resulting in the potential for greater driver error in the decision-making process and increased driver uncertainties, while consistent features allow the driver to drive with minimal effort. In essence, roadway designers want to design roadways that do not surprise drivers or require unexpected operator inputs that might result in erratic driving maneuvers. The design consistency concept is based on this premise.

Although "design consistency" has several aspects, this research project seeks to ascertain how drivers interact with the roadway in a rural environment and, specifically, to identify those roadway features on rural two-lane roadways that can surprise drivers because these features may not conform to the driver's expectations of the roadway.

INTERVIEW QUESTIONS AND RESPONSES

Tables B-2 through B-6 relate the survey questions and the responses that were given.

SUMMARY OF SURVEY RESULTS

The survey of design engineers, consultants, law enforcement personnel, and accident reconstructionists revealed what geometric features these individuals believe are most critical for design consistency. The features were rated on a scale of 1 to 10 (1 being least influential and 10 being most influential); a score of 0 was assigned when respondents did not believe the feature affected design consistency.

The 58 features (e.g., vertical curve and pavement cross-slope) or feature aspects (e.g., radius of horizontal curve and intersection skew angle) had an overall average rating of 3.7, although a relatively clear demarcation was present between features commonly indicated to have a high influence on design consistency and those thought to have a low influence on design consistency.

Tables B-7 through B-18 relate the response rating scores for the 12 individual elements of the survey.

TABLE B-1 Elements contained in the survey

General Elements • Driveways (access points) • Topography (mountainous/rolling/plains) • Tangent length (length of straight section) • Cross-slope (slope across the roadway)	*Horizontal curve* • Presence in general • Radius • Deflection angle (bend) • Length • Superelevation (banking)
Sight distance • Inadequate vs. adequate • Along a roadway • At an intersection	*Shoulder* • Presence • Type (paved/gravel/grass)
Intersections • Presence in general • Skew angle (crossing angle) • Channelization • Lighting • Speed change lanes (refuge lanes)	*Obstructions along the road* • Presence in general • Visual obstruction • Impact problem • Continuous • Intermittent
Median • Presence in general • Type • Width • Transition from no median to median • Transition from median to no median	*Drainage Structures* • Ditch or channel along the roadway • Ditch or channel crossing the roadway • Ditch shape
Vertical curve • Presence in general • Sag • Crest • Sharpness • Length	*Combined Features* • Horizontal and vertical curves • Horizontal curve and an intersection • Vertical curve and an intersection

TABLE B-2 Responses to question 2

2. Are there specific locations that you have encountered where roadway features (e.g., sharp horizontal curves) were the major contributor to crashes or conflicts on rural two-lane roadways? Why?	
Interview #	**Response**
1	• Hidden conflict points that are hidden. SSD alleviate? Some have problem – not enough traffic? SSD may not be enough. • Rumble strips in lane T-intersections may help
2	• Problem when combined with a crest or sag vertical curve. • Inconsistent ISD left vs. right • Sense that it's OK one way so it's OK both. Compare. • Intersections with good ISD but lefts off main poor; gap view from incoming traffic • Skewed intersections turning in or out
3	• Infrequent sharp curves • Paved narrow with no shoulder but straight and high-speed • Close intersections and multi-leg intersections • Construction zones – narrow with barrier on both sides (confinement with no drainage)
4	• Isolated features (inconsistent design) seem to be a problem (i.e., one jug handle, one left exit)
5	• Less than 12 ft [3.7 m] lane (11 ft [3.4 m] with aggregate shoulders get a drop-off with no room for error. (Try to put a 2 ft [0.6 m] bituminous "bumper" with aggregate to eliminate drop-off) • Restricted speed curves – 55 mph [89 km/h] speed limit and don't see signs or otherwise are not ready to react to the presence of the curve at night

6	• Because of inadequate SD
	  • Skewed intersections with bad horizontal alignment
	  • Bad crest vertical curve at intersections

7	• Biggest problem – inconsistent roadway straight section leading into a sharp curve. Dismisses the warning signs. Let people know they need to slow are or correct the curve.
8	• T-intersection signage (on leg). OK if good visibility and daylight, but signs should be used more (relatively cheap). • Sharp curves with poorly placed signage (too far preceding with no follow-up)
9	• Horizontal curve leading to T-intersection. Tried transverse rumble strips, flashing lights, and safety lighting, but did not find a satisfactory solution • Many driveways and intersections are located just beyond crest vertical curves. The cause is sight distance – should provide better. Construct a separate turn lane so school buses could get out of through lane.
10	• Trouble on one good high-speed road. Straight for 5-6 mi [8-9.7 km] then sharp S-Curve. Even locals have problem. Possible super-elevation bad. Tight S-curve. Head-ons and rollover. Surprise after straight stretch.
11	• Speed limit/vehicle speed vs. sight distance (Speed limit set too high for location) at intersections. Speed Limit usually too high with respect to intersections
12	• No. Only confusion is in older drivers who confuse at most normal situation.
13	• Sharp horizontal curves on straight roads (isolated) – reaction too late because of a lack of available preview sight distance. • Intersections where drivers cannot see the intersection. A countermeasure to the problem is providing rumble strips on the minor roadway and flashing lights on the major roadway.
14	• Intersections in general with horizontal curvature or vertical curvature • Shoulder width
15	• Intersections are common location. Drivers must interact.
16	• Does not know of any. Excessive decisions where violate driver expectancies – especially with farm equipment.
17	• Example: road built 25 years ago with 1500 ADT along railroad tracks. At the end of a long tangent a 35-40 mph [56-64.4 km/h] design curve is located. Wrecks at the curve appear to happen because of drivers who are not alert.

TABLE B-3 Responses to question 3

3. Do you believe that certain types of combinations of features (e.g., intersections located near crests of hills) are more likely to be a problem because drivers are surprised or overwhelmed by the driving task? If yes, what combinations? Is this only under certain circumstances? Please describe the feature combinations and any special circumstances.	
Interview #	**Response**
1	• Conflict points hidden by limited stopping sight distance.
2	• Just don't pay attention. Isolated sharp curves with profile change with minimal signing a problem. • Even chevrons border. • Intersections with good ISD but lefts off main poor; gap view from incoming traffic.
3	• Poor SD with improper signing • Intersection SD • Railroad (RR) grade crossings – can't stop RR and can't see – 2 modes • Slippery pavement • (Sight distance?)
4	• Combination of horizontal and vertical curvature • design visualization may help
5	• Driveway entrances onto roadway below crest of hill (also intersections) • School bus stops below crest

6	• Because of inadequate SD
	  • Skewed intersections with bad horizontal alignment
	  • Bad crest vertical curve at intersections

7	• Intersections at vertical curve • Anything that surprises/overwhelms. • Unexpected intersections may distract even if car isn't present. • Straight design leading to sharp curves – "traffic calming." Put in some curvature to indicate change. No change in geometries when going rural to urban.
8	• Crest vertical curve prior to intersections, especially where speed is involved. No solution apparent.
9	• Horizontal and Vertical Curves – drivers surprised. Not necessarily a problem unless driveway or intersection involved. Access management. • Posted Speeds thru horizontal curves too high. Just ignore warning speed/advisory.
10	• Driveway/intersection at hillcrest – should be moved away. Driver error. Lots of hills in west side of District. Vertical curves have bearing on higher-speed roadways.
11	• Speed limit/vehicle speed vs. sight distance (Speed limit set too high for location) at intersections. Speed Limit usually too high with respect to intersections • Sight distance is problem in Tennessee. East side is worst because of terrain
12	• On county roads but infrequently traveled. Can't think of any actual sites. Drivers may be legitimately confused on high-volume roads as they try to keep up with traffic speeds.
13	• Blind intersections past horizontal or vertical curves/driveways/sharp horizontal curve. Can't see upcoming intersections or horizontal curve. Not many, but driveways and intersections can be a problem.
14	• Intersections at crests • On county roads with stop signs, people "blow through" and get hit. Frequently no specific cause can be assigned. • Add or drop lanes on curve
15	• Add or drop lane on curve – task of merging with maneuver on curve.
16	• High. County road intersections near bridge – rail is sight obstruction on flat road, or lots with sharp horizontal curve or vertical curve.
17	• Intersections at crest of hill sometimes cannot be avoided. They may be OK if the sight distance is good • At one end of vertical without good SD problem. Horizontal curve sequence with SD lower on the vertical curve.

TABLE B-4 Responses to question 4

4. Are there situations where certain features (e.g., intersection channelization) might be more likely to surprise drivers or present a problem because of increased driving task difficulty?	
Interview #	**Response**
1	• Can be – freeway forks → driver in wrong lane and last minute change. Attenuators ($) used there in splits (Austin, Dallas) • Driver overload or indecision • Accidents may occur at the conflict points. The results may vary depending on whether a majority of drivers are familiar with the location.
2	• Intersections on back side of hill crests (especially at night)
3	• No response.
4	• Only if applied inconsistently, something out of the blue
5	• Edge stripe absence in wet conditions may be a problem if drivers drive too fast in poor conditions. Our goal is striping that is visible 365 days of the year, although we may lose reflectivity due to snow.
6	• Introducing raised islands too close to thru lanes (say, at a T-intersection). Full shoulder should be carried through intersections.
7	• In rural conditions, transitions between rural and urban to 1st traffic signal. Many places putting up strobe lights to draw attention.
8	• Lack of feature. Long stretches of roads with no opportunity to pass. Helpful – temporary pull-offs for passing at tops of hills.
9	• Highly skewed intersections – can't properly judge the speed of approaching vehicles (at one such location we have had 112 wrecks in 10 years – skewed, horizontal and vertical curves). • Too closely spaced intersections – too much crossing traffic. Not willing to work back off system out to country roads.
10	• 4-lane to a 2-lane. Positioning around other vehicles and run out of lane.
11	• Problem with construction. Surprise because of construction on so many roadways and it changes daily. • If signage is proper, transitions from 2 to 4 lanes is okay. • Too many signs. Need attention getting devices on speed limit signs to draw attention. (Or an inadequate sign in construction)
12	• No. Errors by driver – very simply to drive most intersections even with those histories.
13	• Usually 2 lane increase to 4 lane intersection, but some other use at 2 → 2 lane. Feels the latter is over-designed and unfamiliar drivers hesitate and uncertain. Especially multiple islands/skewed intersections or narrow bridges. Too many islands separating traffic – unnecessary decisions. Especially rural.
13	• Lack of access control.
15	• Too many access points in too close. Farmsteads with multiple points. Wrong choices with U-turns.
16	• Medians with left turn lane – raised. Sometimes use pointed areas for deceleration and surprised by curb. • Enter town – pedestrians, parking, visual demand quickly increases. Access points
17	• Intersection fly-bys that appear after drivers crest hills could be a problem.

TABLE B-5 Responses to question 5

5. The previous questions have focused on two-lane rural highways. Do you have any suggestions regarding other features that might be a problem on higher class rural roadways (e.g., four- or six-lane divided or undivided roadways)?	
Interview #	**Response**
1	• Gore split, but usually urban. Exception: I-35 split at Hillsboro. Northbound on downgrade with good SD – not too much problem. Southbound on I-35W merging into I-35E – Previously no auxiliary lane couldn't tell merge. Similar southbound on 81 where it merges into I-35. No auxiliary lane. Freeway in horizontal curve tilted away.
2	• Short acceleration/deceleration lanes. Older roadways especially if used to longer ones are a problem. • Compound curves on ramps. Too sharp a change from curve 1 to 2.
3	• Lane drops a problem. • Construction is most prominent (as) flaggers with no advance warning. • Ramps • Design speeds different from operating speeds (too much difference) • Sharp curves on urban freeways (bridge – 55 mph [89 km/h] and ramp signed exit only. Signs that appear to be for exit ramps but actually represent conditions on the main lanes).
4	• Consistency related to lane drops/added lanes. Merging vehicles on on-ramps may have a lane or have to make an actual merge into an existing lane.
5	• 5-laning around some cities may lead to transition issues. Lane transitions may surprise when going from 4 lanes to 2 and/or back to 4, especially if on 4-lane for a long time. • 4-lane expressways trying to limit the number of at-grade crossing to focus on expressway operating characteristics.
6	• Different type sections – use care. Make sure selective where using undivided sections – particularly on roadways in the National Highway System.
7	• Lots of divided roadways – shelter in the median for passenger car. SU trucks have more problems without adequate shelter.
8	• Open country – stop lights at major intersections. Warnings – rumble strips and more active warnings (ITS in future) to actively warn driver.
9	• In Panhandle –median opening spacing (insufficient storage between lanes). People create informal crossings.
10	• Intersections are problem. Mississippi 4-lane Biloxi to Jackson. Intersections w/ high speed traffic. Need controlled access to a few locations.
11	• Depends on how DOT classes – no-access/access. If control access and ensure drives are properly located and designed it's okay (sight distance)
12	• People trying to keep up and miss exits. Bifurcations and exit signing could be enhanced and moved back.
13	• Most multilanes have medians. Earlier comments apply, but more options available to driver – wider shoulders, extra lane, median so impacts reduced. Hidden features are still concern but not as serious.
14	• Lots of access points • Continuous two-way left turn lane vs. turn bays – some speeds are high
15	• Rural – close proximity of interchange – weaving probable even through access easier. High demand as enter and approach another.
16	• Super – 2 roadways (i.e., 2-lane roadways with passing lane sections) • 4-lane roadways and priority 3 – people are not looking for entering vehicles on roads that aren't access controlled.
17	• Some designers have problems designing 4 lane roadways without access control. May lay grades with too steep crossover. This can sometimes restrict sight distance (or the guardrail/parapet may do so).

TABLE B-6 Responses to question 6

6. Finally, please provide any additional comments regarding your experiences with improper or poor roadway design in this general topic area. Your input will help establish the direction of this research.	
Interview #	**Response**
1	• Speed consistency – not convinced on high-speed rural roads or of its applicability in urban low-speed settings. • Intersections – most promising. Conflict points have problems if sight distance is restricted • Driver overload – only unfamiliar drivers. Accidents with unfamiliar drivers mostly. If familiar, then overload questionable unless rare event (especially on low ADT intersections). • Conflict points – accident data is "squirrelly" at best. Inconsistent reports can lead to decisions with an inadequate basis.
2	• In my state these problems aren't a design problem – they are historic holdover from older times. Vehicles have progressed but highways have not and cannot change as quickly. • Accident maps can be helpful in diagnosing problems. • Roadways have open travel for miles and then the first stop sign represents a potential problem. Guidance regarding advance signing for that would be helpful.

3	• Corner/curb returns – 15 ft [4.5 m] radius to make turn; must slow down to make the turn.
	• Design consistency – very important.
	• 1st signal into town – a large yellow flashing warning light is used in my state to show when traffic is approaching
	• More comments on questions:
	  • Sharp curves are not bad unless in combination with other features
	  • Skew angle can be treated as a combination with the presence of the intersection
	  • Multiple combinations are worst

4	• Left turn offset is frequently poorly designed. With a car facing you, your vision is obscured; the use of an offset allows a clear view. Typically only a few feet is required. • Prompt – speed changes can be predicted through the application of Mason's work. • Corridors
5	• Bridges that are narrow give a sense of being "squeezed in" when the shoulder is eliminated at the bridge end.
6	• Need guidance on when to fix vertical curve up to current standards. Even 3R guidelines necessitate reconstructing all curves. Hard to get consultants to follow rules of thumb. • If roadways do not meet 3R standards, designers are required to design to full 4R standards, but in some instances this leads to overlapping curves. This requires realignment. • Fixing horizontal curvature problems is usually easier than vertical curvature problems because they do not usually overlap.
7	• No issues.
8	• Not much focus on funding in low volume roadways. Excuses – low funding even though signs are usually low cost. Maintaining signs is cited as a problem. Some people very committed, some people are lax. Dangers of signage not being in place. Little consistency in use of signs.
9	• Design criteria that do not require vertical and horizontal curvature (i.e., intersection of tangents at a point) should be used where appropriate instead of providing minimum-length curves.
10	• Horizontal curves – adequate superelevation is important. • Redundant signing – more than one warning sign should be used in case one is missed. • Intersections – skew less than 90º should be avoided if possible because of reduced neck flexibility in older driver.
11	• With regard to question numbers 2 and 3 – speed and sight distance are major problems (superelevation rarely is a problem). • Intersection sight distance!
12	• My DOT does a very good job of looking at crash history and re-designing intersections if needed. • Greater attention to stop and yield signs to get the attention of drivers.
13	• Combinations of design features with reduced vision increases driver confusion and risk. Reducing the number of hidden combination features should provide benefits along with elimination or red fixed objective in the clear zone along roadway.
14	• Some additional money could have provided a better project for long-term.
15	• Improper or poor design – poor alignment, drainage, ROW, political pressure. Leads to design exceptions but designers cannot always control.
16	• No response.
17	• Intersections at the crest of a hill sometimes cannot be avoided. They can be acceptable if sight distance is good • Horizontal curves with sight distance lower because of a vertical curve can be a problem. • Inconsistency of speeds; sometimes cannot fix (e.g., intersections at crest of hill)

TABLE B-7 Response ratings for general elements

Interview #	Driveways (access points)	Topography (mountainous/rolling/plains)	Tangent Length (length of straight section)	Cross-slope (slope across the roadway)
1	7	6	2	2
2	6	6	2	3
3	0	0	0	0
4	6	7	0	0
5	10	0	0	0
6	9	8	6	5
7	10	0	0	0
8	6	8	3	4
9	7	7	0	0
10	5	8	0	0
11	5	5	1	1
12	0	0	0	0
13	6	5	0	0
14	5	6	4	6
15	9	5	4	6
16	6	0	0	0
17	8	10	2	1
Average	**6.1**	**4.8**	**1.4**	**1.6**

TABLE B-8 Response ratings for site distance

Interview #	Inadequate vs adequate	Along a roadway	At an intersection
1	7	5	7
2	6	8	9
3	0	0	0
4	10	0	0
5	10	0	8
6	7	5	10
7	0	8	0
8	0	0	8
9	0	0	5
10	5	0	6
11	10	2	5
12	0	0	0
13	8	6	9
14	9	6	9
15	8	4	7
16	10	8	10
17	8	7	8
Average	**5.8**	**3.5**	**5.9**

TABLE B-9 Response ratings for intersections

Interview #	Presence in general	Skew angle (crossing angle)	Channelization	Lighting	Speed Change Lanes (dec/acc lanes)	Spacing between intersection	Left Turn Lane Offset	Left Turn lane Length
1	6	5	2	1	3	2	2	3
2	5	7	5	5	5	5	8	3
3	0	0	0	0	0	0	0	0
4	0	0	0	0	0	6	9	0
5	0	0	9	10	9	0	0	0
6	8	9	6	6	6	8	6	6
7	8	5	0	0	0	0	0	0
8	9	4	3	4	4	3	3	5
9	0	10	0	5	3	7	0	3
10	5	6	0	5	0	0	0	0
11	7	1	2	2	5	5	2	8
12	0	0	0	0	0	0	0	0
13	5	3	0	0	0	7	3	4
14	5	7	5	5	5	8	4	5
15	10	9	8	4	6	7	5	3
16	5	6	4	3	3	5	5	5
17	2	5	2	0	3	3	5	3
Average	**4.4**	**4.5**	**2.4**	**2.9**	**2.7**	**3.9**	**3.1**	**2.8**

TABLE B-10 Response ratings for median

Interview #	Presence in General	Type	Width	Transition from no median to median	Transition from median to no median
1	2	1	3	1	1
2	2	2	2	3	3
3	0	0	0	0	0
4	0	0	0	0	0
5	0	0	0	0	0
6	7	6	8	6	9
7	0	0	0	0	0
8	6	7	4	4	3
9	0	0	0	0	0
10	0	0	0	3	6
11	2	5	2	2	2
12	0	0	0	0	0
13	0	0	0	3	2
14	4	4	4	5	5
15	4	4	4	4	4
16	5	5	5	5	5
17	0	0	0	0	0
Average	**1.9**	**2.0**	**1.9**	**2.1**	**2.4**

TABLE B-11 Response ratings for vertical curve

Interview #	Presence in general (VC)	Sag	Crest	Sharpness	Length
1	7	3	7	6	6
2	2	2	2	7	2
3	0	0	0	0	0
4	0	0	3	5	2
5	0	0	0	0	0
6	5	6	8	6	9
7	0	0	0	8	0
8	0	2	8	7	3
9	0	5	7	0	0
10	5	0	7	0	0
11	0	0	0	0	0
12	0	0	0	0	0
13	3	4	5	7	0
14	4	4	6	7	4
15	7	4	8	6	5
16	5	2	5	8	2
17	3	1	6	7	7
Average	**2.4**	**1.9**	**4.2**	**4.4**	**2.4**

TABLE B-12 Response ratings for horizontal curve

Interview #	Presence in General II	Radius	Deflection Angle (bend)	Length (HC)	Superelevation (banking)	Vision through curve
1	6	6	5	3	5	6
2	2	6	2	2	5	6
3	0	0	0	0	0	0
4	5	6	6	0	0	7
5	0	0	0	0	10	0
6	5	10	5	5	10	5
7	0	4	0	7	0	7
8	7	6	5	3	6	8
9	5	0	0	0	5	5
10	5	3	0	0	3	3
11	5	7	4	2	5	8
12	0	0	0	0	0	0
13	5	8	7	5	4	9
14	6	8	8	6	8	8
15	9	8	5	6	10	7
16	5	6	6	5	5	7
17	5	7	7	7	5	7
Average	**4.1**	**5.0**	**3.5**	**3.0**	**4.8**	**5.5**

TABLE B-13 Response ratings for passing lanes

Interview #	Presence	Transitions	Length (PL)	Presence at intersection
1	3	2	5	6
2	4	4	4	8
3	0	0	0	0
4	0	0	5	9
5	10	0	0	0
6	6	4	5	4
7	7	0	0	6
8	7	4	8	8
9	7	0	8	0
10	0	3	5	0
11	5	5	2	8
12	0	0	0	0
13	0	3	2	0
14	5	7	7	10
15	6	7	5	8
16	6	6	6	7
17	5	4	4	10
Average	**4.2**	**2.9**	**3.9**	**4.9**

TABLE B-14 Response ratings for shoulder

Interview #	Presence (SH)	Type (paved/gravel/grass)	Width (SH)
1	6	5	5
2	6	2	6
3	0	0	0
4	0	0	0
5	0	0	0
6	9	6	7
7	0	0	0
8	8	8	5
9	0	5	0
10	0	5	0
11	5	5	5
12	0	0	0
13	6	2	5
14	10	5	10
15	4	5	6
16	5	6	8
17	8	0	0
Average	**3.9**	**3.2**	**3.4**

TABLE B-15 Response ratings for obstructions along the road

Interview #	Presence in general (SH)	Visual obstruction	Impact Problem	Continuous (berms, barriers, etc)	intermittent (trees, rocks, shrubs, etc)
1	3	6	2	2	2
2	3	7	3	3	3
3	0	0	0	0	0
4	3	0	0	0	0
5	0	10	0	0	0
6	5	5	9	6	8
7	0	0	0	0	0
8	7	8	7	5	8
9	7	6	0	0	0
10	4	7	0	0	3
11	5	5	5	2	2
12	0	0	0	0	0
13	8	8	8	4	8
14	7	7	9	6	7
15	8	9	7	6	5
16	6	8	7	5	6
17	5	8	0	1	3
Average	**4.2**	**5.5**	**3.4**	**2.4**	**3.2**

TABLE B-16 Response ratings for drainage structures

Interview #	Ditch or channel along the roadway	Ditch or channel crossing the roadway	Ditch Shape
1	1	1	1
2	3	2	1
3	0	0	0
4	7	4	5
5	0	0	0
6	3	2	2
7	10	9	0
8	4	3	3
9	0	4	5
10	0	0	0
11	2	5	2
12	0	0	0
13	2	4	2
14	4	4	6
15	2	3	1
16	3	3	3
17	0	1	2
Average	**2.4**	**2.6**	**1.9**

TABLE B-17 Response ratings for combined features

Interview #	Horizontal and vertical curves	Horizontal curve and an intersection	Vertical Curve and an intersection	Vertical Curve and horizontal curve and an intersection
1	7	7	8	8
2	10	8	10	10
3	0	0	0	0
4	7	7	7	9
5	0	0	0	0
6	9	9	9	10
7	0	0	10	10
8	7	9	8	9
9	8	8	8	8
10	4	4	8	8
11	2	2	2	2
12	0	0	0	0
13	7	8	8	9
14	7	8	7	9
15	9	7	8	10
16	5	8	7	9
17	10	10	10	10
Average	**5.4**	**5.6**	**6.5**	**7.1**

TABLE B-18 Response ratings for traffic control devices

Interview #	Lane Markings (paint, buttons, etc)	Passing/ no passing markings	Lane Marking transitions	Intersection delineation	Lane Assignment signs (allowed use) at intersections	Advisory Speed Limit Signs	Regulatory Speed limit Signs	Guide signs (destination/ route signs)
1	2	1	1	3	1	0	2	3
2	2	3	6	8	6	2	2	2
3	0	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0	0
5	10	10	0	0	0	0	0	0
6	8	8	5	5	3	4	5	2
7	0	0	0	0	0	0	0	0
8	6	8	5	7	4	4	6	4
9	0	5	0	6	5	0	0	5
10	8	9	0	7	3	5	5	4
11	10	6	10	5	5	1	10	8
12	0	5	0	0	0	0	5	0
13	3	4	3	4	4	3	0	4
14	8	10	10	8	7	6	8	7
15	8	7	10	6	9	4	5	3
16	6	7	3	5	5	4	6	5
17	1	1	1	1	1	1	1	1
Average	**4.2**	**4.9**	**3.2**	**3.8**	**3.1**	**2.0**	**3.2**	**2.8**

APPENDIX C

SURVEY ON DEFINITIONS

DESIGN CONSISTENCY

Design Consistency Background Information

Design consistency has been the subject of several research studies. These studies have used various measures in attempts to examine the consequences of inconsistencies on safety and operations. A wide variety of roadway features and characteristics have been examined, including the following:

- Horizontal curve radius and deflection angle;
- Vertical curve sharpness;
- Individual features, such as left-hand exits;
- Closely spaced or overlapping features;
- Divergences between the roadway alignment and parallel features (i.e., a fence line that diverges from the roadway at a horizontal curve); and
- Lane drop patterns and so forth.

Measures used in the study of design consistency include the following:

- **Consistency of speed.** As drivers proceed along a roadway, it is desirable that their speeds remain relatively constant as they traverse the roadway.
- **Driver workload.** Similar to speed, it is desirable that driver workload remain relatively constant as drivers proceed along a roadway.
- **Safety.** Safety measures have often been examined to determine the validity of consistency models.

Current definitions related to design consistency are unclear, difficult to apply, and include language that can be difficult to explain and defend. The survey sought to identify a preferred definition of “design consistency.” Table C-1 lists the definitions provided to survey participants and the number of participants who selected each definition. Tables C-2 through C-7 contain comments or concerns expressed by the respondents and alternative definitions provided.

The survey was conducted through a mailing to each of the state DOTs and the research panel. Some of the DOTs chose to provide multiple responses. The characteristics of the respondents are provided in Table C-8.

SURVEY DEFINITIONS AND RESULTS

Tables C-2 through C-7 display the comments given by survey participants.

RESPONDENT CHARACTERISTICS

Table C-8 provides respondent characteristics.

TABLE C-1 Definitions contained in survey and number of responses

Design Consistency is…	Number of Responses
1. The conformance of a highway's geometric and operational features with driver expectancy.	19
2. The avoidance of abrupt changes in geometric features for continuous highway elements and the more careful use of design elements to meet driver expectancies.	4
3. The agreement of the geometric and operational aspects of the roadway with driver expectancy.	5
4. The similarity in appearance and function of roadway features to previous features encountered by the driver.	3
5. The lack of abrupt changes in geometric features that might affect driver behavior for contiguous highway elements and design elements in combination.	2
6. The uniformity of operating speed observed in the speed profile of individual motorists traversing a section of roadway.	2
7. The limiting of the driver's workload imposed by geometric features or combinations of adjacent geometric features.	1
8. Alternate definition	17

TABLE C-2 Concerns/comments received on definition 1

DESIGN CONSISTENCY is the conformance of a highway's geometric and operational features with driver expectancy	
Interview #	**Comments/Concerns**
16	The selected definition is brief yet concise. I would and do find it very helpful.
23	The Utah Department of Transportation uses approved design standards to maintain a consistency in design.
26	Are safety features considered part of the geometric or operational features?
44	A simple definition is probably the best with additional text and graphics to support the concept.
51	Design consistency is the conformance of a highway's geometric and operational features with driver expectancy in a given environment
52	I prefer the first definition for its simplicity. The sixth definition has appeal in the sense that there's some promise of a means of measuring design consistency under that definition. I have no strong preference among these.

TABLE C-3 Concerns/comments received on definition 3

DESIGN CONSISTENCY is the agreement of the geometric and operational aspects of the roadway with driver expectancy.	
Interview #	**Comments/Concerns**
29*	Providing consistency in design is a desirable quality. However, from a practical standpoint it is not always feasible to accomplish this quality on a continuous basis by geometric alone. Where significant geometric changes occur, designer must use other tools such as signing, geometric transitions, and visual reinforcement to enhance driver expectancy.
30*	Providing consistency in design is a desirable quality. However, from a practical standpoint it is not always feasible to accomplish this quality on a continuous basis by geometric alone. Where significant geometric changes occur, designer must use other tools such as signing, geometric transitions, and visual reinforcement to enhance driver expectancy.

* Respondents collaborated to provide a consensus comment.

TABLE C-4 Concerns/comments received on definition 4

DESIGN CONSISTENCY is the similarity in appearance and function of roadway features to previous features encountered by the driver.	
Interview #	**Comments/Concerns**
8	I am concerned less about the definition than I am about how it is measured, modified, and used in decision making.

TABLE C-5 Concerns/comments received on definition 5

DESIGN CONSISTENCY is the lack of abrupt changes in geometric features that might affect driver behavior for contiguous highway elements and design elements in combination.	
Interview #	**Comments/Concerns**
9	(Marked Definition 4 as second choice.) There can be a “narrow” geometric definition and a “broader” definition which includes operations (e.g., signals) and abutting land use factors.
14	To me, this defines it more clearly what our intent is as a designer. We are designing to how a driver will behave as well as what a driver’s expectancy is. I wouldn’t mind just adding “where driver expectancy is met.” Or something like that. I was a close second on “the conformance of a highway’s geometric and operational features with driver expectancy,” but I like the more thoroughness of the one I prefer.

TABLE C-6 Concerns/comments received on definition 6

DESIGN CONSISTENCY is the uniformity of operating speed observed in the speed profile of individual motorists traversing a section of roadway.	
Interview #	**Comments/Concerns**
42	Operating speed is a reflection of driver expectations. [This is a] measurable attribute of consistency. A combination of alternatives is what I purpose, one that has geometrics and how observable both included. The similarity in appearance of geometric features over a section of roadway such that uniform operating speeds are observed.
48	I suggest this definition because it provides a measure /it is not qualitative only.

TABLE C-7 Alternative definitions

Interview #	Suggested Definition/Comments
3	• Design consistency is the avoidance of abrupt changes in the operational aspects of the roadway through the judicious use of design elements to meet driver expectations. • Since operational consistency is what we're really looking for and because the operation is directly related to the geometrics, I feel that any of the definitions that include both "operation" and "geometric" are redundant.
7	• Possibly a definition that combines Definition 3 (the agreement of the geometric and operational aspects of the roadway with driver expectancy) and Definition 4 (the similarity in appearance and function of roadway features to previous features encountered by the driver) checked above.
10	• Design consistency is the consistent application of proven design practices that produces consistent driver behavior on similar roadways.
17	• Design consistency is the similarity of a highway's geometric and operational features meeting a driver's expectancy within a given section of highway.
20	• Combine the first/fourth: Design consistency is the similarity in appearance and function of a highway's geometric and operational features to previous features encountered by the driver. • "Conform" could be risky – too many drivers with too many expectancies • "Uniform" may be difficult – too many variables in design location that may not allow for designs to be exactly the same – limits context design.
21	• Design consistency is the conformance of geometric and operational features of a highway to the roadway system, roadside area, and driver expectation. • Any definition that is ultimately agreed on must take into account the expectation of the driver and those conditions through which he travels. The compatibility of the design to that role expected of the roadway is critical.
28	• Design consistency is the application of standard geometric and operational features to a roadway ensuring driver expectancies are met.
33	• Design consistency is the conformance of a highway's geometric and operational features with driver expectancy without abrupt changes for continuous highway elements. • The above definition combines the first two definitions and captures the definition as I see it.
35, 36, 37	• Design consistency is the avoidance of abrupt changes in geometric and operational features for continuous highway design elements and the careful selection of design elements that meet driver expectancies.
38	• (Combination of 2 & 5) Design consistency is the avoidance of abrupt changes in geometric features that may adversely affect driver behavior. • Keep the definition simple and then follow with additional discussion of how driver expectations change with speed, terrain, functional class, etc. • The word "adversely" affect driver behavior is needed, i.e., Reconstruction of a segment of old to new but could adversely affect drivers going from new to old.
39, 40, 41	• Design consistency is an arrangement of highway features that minimize the potential for adverse driver reactions due to surprise or misinterpretation. • NYSDOT does not have a definition for 'design consistency' • Concern: Drivers may be too unique (i.e. they run the gamut of abilities and personalities) to get a useful or uniform definition
45	• Design consistency is the similarity of a highway's geometric and operational features meeting a driver's expectancy within a given section of highway.
47	• Design consistency is a facility designed with all elements in balance, consistent with an appropriate design speed (Note [*From Interviewee*]: If designers use existing design guidelines for each type of facility, design consistency will result. The above are awfully fluffy and fuzzy sounding "definitions". Is this engineering or sociology?

TABLE C-8 Respondent characteristics

Response	State	Group	Years in Design	Years in Operations	Various
1	VA	State	37		
2	VT	State	23		
3	ID	State	10	11	
4	TX	State			17
5	VA	State	18		
6	LA	State	27		
7	WY	State	25	5	
8	WA	State	20		
9	AR	Panel	5	2	
10	LA	State			
11	MS	State	30	2	
12	VA	Panel	5	30	
13	VA	Panel			
14	SD	State	16	4	
15	SC	State			
16	MO	State	16	2	
17	WV	State	15		
18	NH	State	25		
19	AR	State	31		
20	NV	State	10	1	
21	KY	State	32	0	
22	IL	State	13		
23	UT	State	15	10	
24	NC	State	30	0	
25	ND	State	30		
26	IA	State	9.5		
27	WV	State	40		
28	FL	State			27
29	KS	State	31	20	
30	KS	State	30		
31	WI	State	15		
32	MN	Panel	40		
33	AL	State	17		
34	TX	Panel			17
35	NJ	State	33		
36	NJ	State	33		
37	NJ	State	33		
38	AZ	State	30		
39	NY	State	30	1	
40	NY	State			
41	NY	State			
42	MN	State	25		
43	GA	Panel	17		
44	MA	State	26		
45	WV	State	15		
46	MI	State	13	13	
47	TX	State			
48	PA	Researcher			
49	WI	State			
50	TN	State	17		
51	FL	State	15		

APPENDIX D
CASE STUDIES

Three case studies were completed to review the design consistency rules. The sites were selected to meet the following criteria:

- Rolling terrain,
- Moderate traffic volumes,
- Rural conditions,
- High-speed traffic, and
- Collectively, cover a range of initial time of construction.

State DOT personnel in two states (Oklahoma and Texas) were contacted to obtain information regarding candidate sites. Researchers examined the roadways by doing the following:

- Reviewing construction plans,
- Videotaping the roadway segment,
- Locating driveways, and
- Measuring speeds of free-flow vehicles.

Speed measurements were obtained using a lasergun; 100 free-flow vehicles were measured at each site. The speeds were measured on sections with moderate (<2%) grades and tangent horizontal alignments. Test sections 5–7 km [3–4.5 mi] in length were selected for evaluation, providing various features and roadway characteristics.

CASE STUDY A

Case study A was completed on a roadway originally constructed as a county roadway and upgraded with a paved surface in the 1940s. The basic alignment of the roadway was not substantially modified. The design speed used to establish the vertical and horizontal alignment was not recorded in the available plans. The traffic volume on the roadway is estimated at 3,000 vehicles per day (vpd). The case study focused on a 5.5 km [3.4 mi] section of the roadway extending from a small unincorporated community of approximately 150 to a bridge over a creek.

The roadway consists of a 5.5 m [18 ft] paved surface with 1 m [3 ft] tapered base shoulders and an additional variable turf shoulder that is not readily apparent in the field. Figure D-1 provides a view typical of the roadway.

Speeds on the roadway were relatively high (see Figure D-2), with an 85th percentile speed of 114 km/h [71 mph]. The posted speed limit on the roadway is 113 km/h [70 mph] day and 105 km/h [65 mph] night for passenger vehicles and 97 km/h [60 mph] day and 89 km/h [55 mph] night for trucks. A short section passing through a very small community on the roadway was posted at 89 km/h [55 mph] for all vehicles.

Application of Design Consistency Rules

Cross Section

The rules related to cross section (i.e., *reduction in lane width, reduction in shoulder width, lane drop with major driveway*, and *major driveway and lane addition*) did not detect any inconsistencies because the cross section remained constant throughout the test section.

Horizontal Alignment

The rule *tight horizontal curve with wide shoulders* did not detect any inconsistencies because the shoulder width remained constant throughout the test section.

Vertical Alignment

The rule *steep downgrades* was applied to four different grades on the alignment. The steepest and longest grade was 4.6% and 213 m [700 ft] long; however, this did not meet the minimum grade requirement of 5% and 900 m [2,950 ft].

Highway-Railroad Grade Crossing

The rule *highway-railroad grade* crossing was not applied because no railroad grade crossings were present on the roadway.

Driveways

The rules *access points or frequency of driveways—speed differential* and *access points or frequency of driveways—accident potential* were applied to the test section. The test section had 7 driveways/km, the section north of the test section had 11 driveways/km, and the section south of the test section had 7 driveways/km. The differences of 4 and 0, respectively, did not trigger the Level 2 threshold of 8 driveway access points per kilometer more than the previous segment.

The rule *minimum separation between driveways* was applied to the test section. The plans used for the consistency assessment were developed in the 1940s and have not been

Figure D-1. Case Study A roadway.

updated. Observation revealed that the driveways were spaced more closely in a number of instances than the minimum spacing of 84 m [275 ft] indicated for a highway speed of 80 km/h [262 mph] (the maximum shown in the rule table). Accordingly, the warning messages were applicable:

The spacing between the driveways at Stations XXX + XXX and YYY + YYY on the left side of the road may be too small.

The spacing between the driveways at Stations XXX + XXX and YYY + YYY on the right side of the road may be too small.

If limited to commercial or major driveways, the warning would not have been triggered.

The rule *offset opposing driveways* was applied to the test section. Again, based on observation, the warning message was applicable:

The separation distance between the offset opposing driveways at Stations XXX + XXX and YYY + YYY may be too short to provide sufficient weaving distance and left-turning storage length. The driveways should either be located opposite one another or should be offset by at least 91 m [300 ft].

If limited to commercial or major driveways, the warning would not have been triggered.

Climbing and Passing Lanes

The rule *climbing lane needed but not provided* was applied to the test section. The grades present would not be sufficiently long or steep to trigger a warning message.

The rule *climbing lane not carried over crest* was not applied to the test section because climbing lanes were not present.

Next, the rule *insufficient passing opportunities* was applied to the test section. The equation related to net passing opportunities was utilized:

$$\mathrm{NPO} = (100 - 100\,\mathrm{APL})(\mathrm{APZ}e^{-0.0018626\,\mathrm{OFLOW}}) + 100\,APL, \quad (1)$$

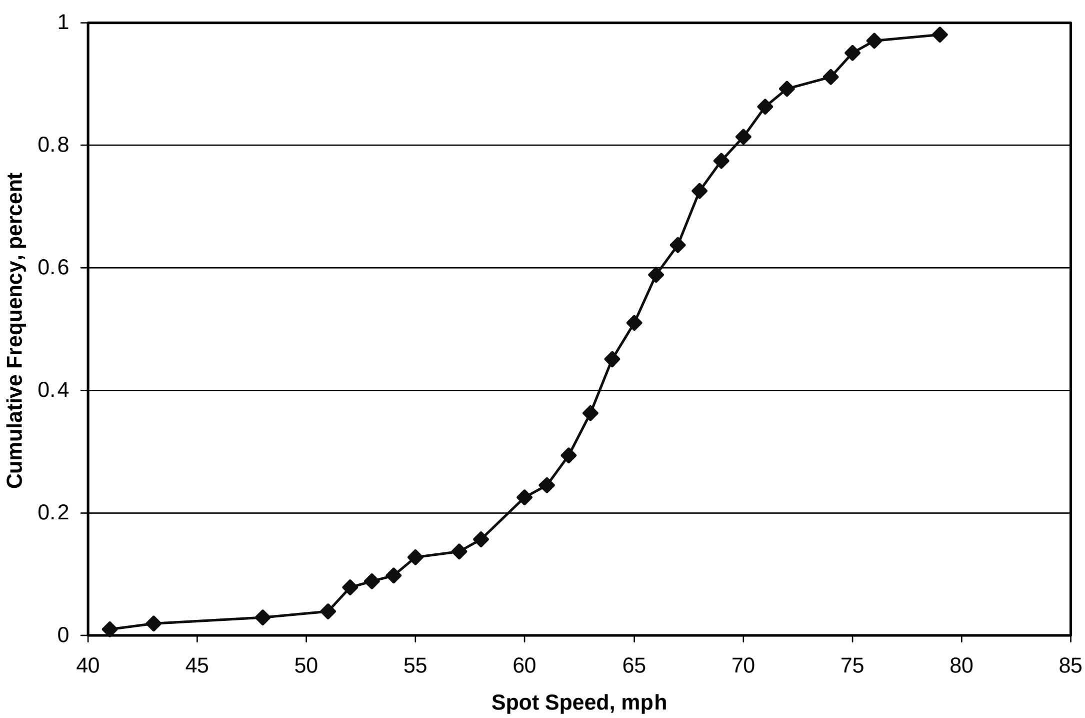

Figure D-2. Cumulative speeds, Case Study A.

where

NPO = percentage of net passing opportunities
APZ = proportion of segment length with marked passing zones (not including areas with passing or climbing lanes in the study direction)
APL = proportion of segment length with passing or climbing lanes in study direction
OFLOW = opposing flow rate (veh/h) during peak-flow in the study direction

Opposing flow was obtained through the use of the provided ADT (3,000 vpd) and the following equation:

$$\text{DDHV} = (\text{ADT})(K)(D), \tag{2}$$

where:

DDHV = daily design hourly volume (veh/h)
ADT = average daily traffic (veh/h)
K = average daily traffic occurring in the design hour (percent)
D = directional distribution (percent)

For an actual design, values for K and D would be estimated using standard planning techniques and typically would be provided to the designer. For this case study, they were estimated at

$K = 15\%$

$D = 50\%$

Using these values and the ADT of 3,000 vpd, DDHV was estimated at 225 veh/h (and thus the OFLOW value). Substituting the characteristics of the study site:

$APZ_{NB} = 41\%$

$APZ_{SB} = 59\%$

APL = 0

OFLOW = 225

Using these values in the consistency equations provides a value for NPO of 27% for the NB direction and 39% for the SB direction. Accordingly, the following Level 2 warning message was appropriate:

Supply of passing opportunities between Stations XXX + XX and YYY + YY may be insufficient. An LOS investigation using the HCM procedures for two-lane highways is recommended.

The following rules were not applied because no passing lanes were present: *passing lane too short*, *passing lane too long*, and *passing lane addition channels slow vehicles into left lane.*

Frequency of Decisions on Roadway Segments

The test section was reviewed for the presence of the following features to test the rule *frequency of decisions on roadway segments:*

- Intersection [present];
- Major driveway [not present];
- Railroad-highway grade crossing [not present];
- Beginning or end of a horizontal curve with radius less than 800 m [2,600 ft] [present];
- Vertical curve with available SSD less than that given in the Green Book for a design speed equal to 20 km/h [10 mph] less than the roadway operating speed [present];
- School zone [not present];
- Narrow bridge (curb-to-curb width less than the roadway approach including paved shoulder) [not present];
- Change in posted speed limit [present];
- Lane addition [not present];
- Lane drop [not present];
- Lane width reduction by 0.6 m [2 ft] or more [not present]; and
- Shoulder width reduction by 1.2 m [4 ft] or more [not present].

One location was examined to see if the cluster had four features that met the criteria given in a segment of 450 m [1,500 ft]. The location, on the outskirts of an unincorporated community, had a vertical curve, speed limit change, and two street intersections within 450 m [1,500 ft]. Accordingly, the following Level 2 warning message would be appropriate:

The roadway segment from Station XX + XXX to YY + YYY contains more than four geometric design or traffic control elements that require driver decisions. Consideration should be given to spacing these decisions over a longer roadway length, if practical.

Preview Sight Distance

The test section was reviewed for the presence of the following features:

- School zones,
- Passing/climbing lane drops,
- Narrow bridges,
- Lane width reductions,
- Shoulder width reductions,

- Railroad-highway grade crossings, and
- Major driveways.

None of the features were present on the test section, so the rule was not applied.

CASE STUDY B

This case study was completed on a roadway constructed in the late 1930s. Although the roadway has been resurfaced numerous times, the basic alignment has not been modified. The design speed used to design the roadway was not recorded in the available plans. Because the roadway is scheduled for reconstruction, the traffic volume used in the case study is the 20-year design projection, 5600. The directional distribution of 60-40% and a *K* factor of 10.8% were provided with the traffic projection. A 7 km [4.5 mi] section was selected for evaluation using the design consistency rules.

The roadway consists of a 10.3 m [34 ft] paved surface with 3.6 m [12 ft] lanes and 1.5 m [5 ft] shoulders. Figure D-3 provides a typical view of the roadway.

Speeds on the roadway were relatively high (see Figure D-4), with an 85th percentile speed of 116 km/h [72 mph]. The posted speed on the roadway is 113 km/h [70 mph] day and 105 km/h [65 mph] night for passenger vehicles and 97 km/h [60 mph] day and 89 km/h [55 mph] night for trucks.

Figure D-3. Case Study B roadway.

A short section passing through a very small unincorporated community is posted at 97 km/h [60 mph] for all vehicles.

Application of Design Consistency Rules

Cross Section

The rules related to cross section (i.e., *reduction in lane width, reduction in shoulder width, lane drop with major*

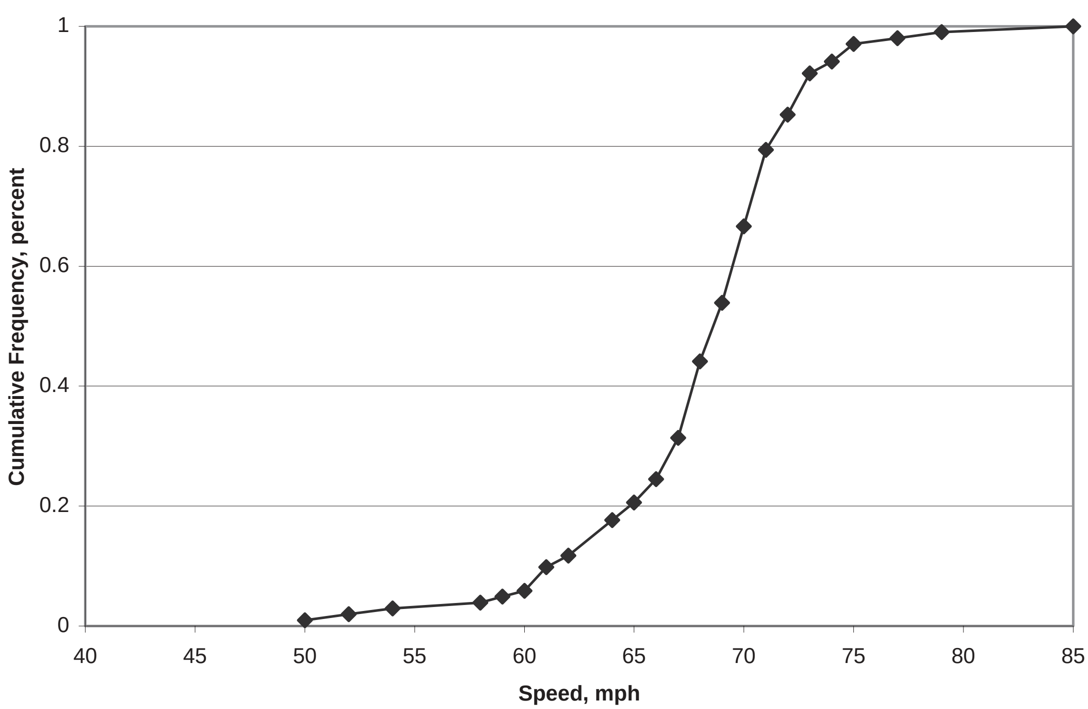

Figure D-4. Cumulative speeds, Case Study B.

driveway, and *major driveway and lane addition*) did not detect any inconsistencies because the cross section remained constant throughout the test section.

Horizontal Alignment

The rule *tight horizontal curve with wide shoulders* did not detect any inconsistencies because the shoulder width remained constant throughout the test section.

Vertical Alignment

The rule *steep downgrades* was applied to four different grades on the alignment. The steepest and longest grade was 3.3% and 600 ft [183 m] long; however, this did not meet the minimum grade requirement of 5% and 2,951 ft [900 m].

Highway-Railroad Grade Crossing

The rule *highway-railroad grade* crossing was not applied because no grade crossings were present on the roadway.

Driveways

The rules *access points or frequency of driveways—speed differential* and *access points or frequency of driveways—accident potential* were applied to the test section. The test section had 3 driveways/km [1.9 driveways/mile], the section east of the test section had 3.7 driveways/km [2.3 driveways/mile], and the section south of the test section had 1.7 driveways/km [1 driveway/mile]. The differences of 0.7 and 1.3, respectively, did not trigger the Level 2 Threshold of 8 driveway access points per kilometer more than the previous segment.

The rule *minimum separation between driveways* was applied to the test section. The plans used for the consistency assessment were developed in the 1930s and have not been updated. Observation revealed that the driveways in the unincorporated town were spaced more closely in a number of instances than the minimum spacing of 84 m [275 ft] indicated for a highway speed of 80 km/h [50 mph] (the maximum shown in the rule table). Accordingly, the warning messages were applicable:

> *The spacing between the driveways at Stations XXX + XXX and YYY + YYY on the left side of the road may be too small.*

> *The spacing between the driveways at Stations XXX + XXX and YYY + YYY on the right side of the road may be too small.*

If limited to commercial or major driveways, the warning would not have been triggered.

The rule *offset opposing driveways* was applied to the test section. Again, based on observation, the Level 2 warning message was applicable:

> *The separation distance between the offset opposing driveways at Stations XXX + XXX and YYY + YYY may be too short to provide sufficient weaving distance and left-turning storage length. The driveways should either be located opposite one another or be offset by at least 91 m [300 ft].*

If limited to commercial or major driveways, the warning would not have been triggered.

Climbing and Passing Lanes

The rule *climbing lane needed but not provided* was applied to the test section. The grades present would not be sufficiently long or steep to trigger a warning message.

The rule *climbing lane not carried over crest* was not applied to the test section because climbing lanes were not present.

The rule *insufficient passing opportunities* was applied to the test section. Using Equations 1 and 2, net passing opportunities were assessed. These values were used in the equations:

$APZ_{EB} = 0.42$

$APZ_{WB} = 0.54$

$APL = 0$

$ADT = 5{,}600$

$K = 10.8\%$

$D = 60\%$

Using Equation 1:

$NPO_{EB} = 0.21$

$NPO_{WB} = 0.27$

Accordingly, the following Level 2 warning message was appropriate:

> *Supply of passing opportunities between Stations XXX + XX and YYY + YY may be insufficient. An LOS investigation using the HCM procedures for two-lane highways is recommended.*

The following rules were not applied because no passing lanes were present: *passing lane too short*, *passing lane too long*, and *passing lane addition channels slow vehicles into left lane*.

Frequency of Decisions on Roadway Segments

The test section was reviewed for the presence of the following features to test the rule *frequency of decisions on roadway segments*:

- Intersection [present];
- Major driveway [not present];
- Railroad-highway grade crossing [not present];
- Beginning or end of a horizontal curve with radius less than 800 m [2,600 ft] [not present];
- Vertical curve with available SSD less than that given in the Green Book for a design speed equal to 20 km/h [10 mph] less than the roadway operating speed [present];
- School zone [not present];
- Narrow bridge (curb-to-curb width less than the roadway approach including paved shoulder) [not present];
- Change in posted speed limit [present];
- Lane addition [not present];
- Lane drop [not present];
- Lane width reduction by 0.6 m [2 ft] or more [not present]; and
- Shoulder width reduction by 1.2 m [4 ft] or more [not present].

Although several of the individual critical features were present, their locations were sufficiently separated that no warnings were generated.

Preview Sight Distance

The test section was reviewed for the presence of the following features:

- School zones,
- Passing/climbing lane drops,
- Narrow bridges,
- Lane width reductions,
- Shoulder width reductions,
- Railroad-highway grade crossings, and
- Major driveways.

None of the features were present on the test section, so the rule was not applied.

CASE STUDY C

This case study was recently reconstructed, thus providing an example of a recently completed project. The alignment was upgraded to current DOT standards in the late 1990s. The traffic volume for the roadway is 2,800 vpd in the design year and represents a 20-year traffic projection. A section 6 km [3.7 mi] in length was selected for evaluation using the design consistency rules.

The roadway has 3.6 m [11.8 ft] lanes and 2.4 m [7.9 ft] shoulders. Figure D-5 provides a typical view of the roadway.

Speeds on the roadway were similar to the other case studies, with an 85th percentile speed of 111 km/h [69 mph] (see Figure D-6). The posted speed limit on the roadway is 105 km/h [65 mph]. A speed limit of 89 km/h [55 mph] is posted at the end of the test section near the city limit of a small town.

Application of Design Consistency Rules

Cross Section

The rules related to cross section (i.e., *reduction in lane width, reduction in shoulder width, lane drop with major driveway*, and *major driveway and lane addition*) did not detect any inconsistencies because the cross section remained constant throughout the test section with the exception of a short widening for a deceleration lane. The deceleration lane occupied the shoulder with only a nominal widening (2.4 m [7.9 ft] shoulder widened to 3.6 m [11.8 ft] deceleration lane).

Horizontal Alignment

The rule *tight horizontal curve with wide shoulders* did not detect any inconsistencies because the shoulder width remained constant throughout the test section with the sole exception described under *Cross Section*.

Vertical Alignment

The rule *steep downgrades* did not generate any warnings because the steepest grade present on the roadway, 4.6%, did not meet the minimum grade requirement of 5%.

Figure D-5. Typical view of roadway, Case Study C.

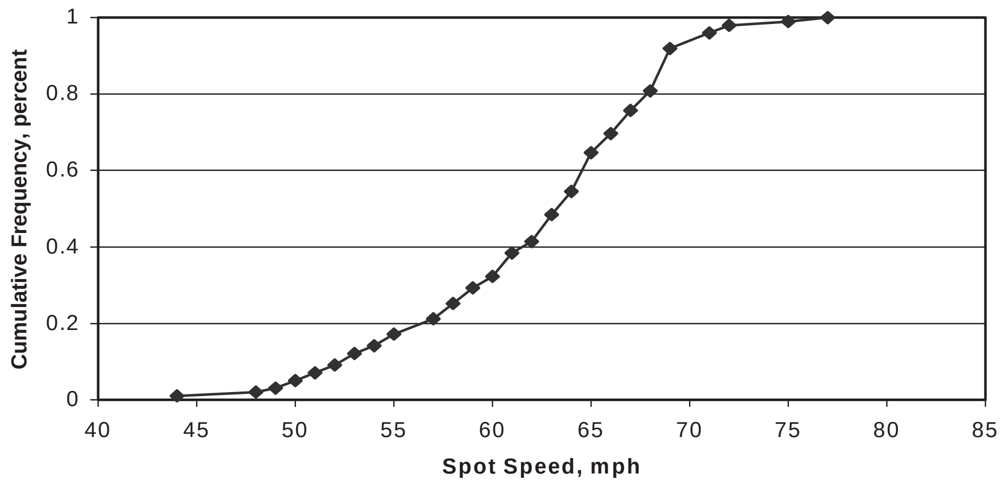

Figure D-6. Cumulative speeds, Case Study C.

Highway-Railroad Grade Crossing

The rule *highway-railroad grade* crossing was not applied because no railroad grade crossings were present on the roadway.

Driveways

The rules *access points or frequency of driveways—speed differential* and *access points or frequency of driveways—accident potential* were applied to the test section. The test section had 4.0 driveways/km [2.5 driveways/mi] and the section north of the test section had 3.4 driveways/km [2.1 driveways/miles], a difference of 0.6 km [0.4 miles]. The section south of the test section was an incorporated town so no comparison was developed. The difference of 0.6 did not trigger the Level 2 threshold of 8 driveway access points per kilometer more than the previous segment.

The rule *minimum separation between driveways* was applied to the test section. Driveways in one area violated the minimum spacing of 84 m [275 ft]. Accordingly, the warning message was applicable:

> *The spacing between the driveways at Stations XXX + XXX and YYY + YYY on the left side of the road may be too small.*

The driveways in question were commercial in nature and could reasonably be expected to generate moderate traffic.

The rule *offset opposing driveways* was applied to the test section. Two areas violated the criteria, justifying the following warning message:

> *The separation distance between the offset opposing driveways at Stations XXX + XXX and YYY + YYY may be too short to provide sufficient weaving distance and left-turning storage length. The driveways should either be located opposite one another or should be offset by at least 91 m [300 ft].*

If limited to commercial or major driveways, the warning would not have been triggered.

Climbing and Passing Lanes

The rule *climbing lane needed but not provided* was applied to the test section. The grades present would not be sufficiently long or steep to trigger a warning message.

The rule *climbing lane not carried over crest* was not applied to the test section because climbing lanes were not present.

The rule *insufficient passing opportunities* was applied to the test section. Using Equations 1 and 2, net passing opportunities were assessed. These values were used in the equations:

$APZ_{EB} = 0.58$

$APZ_{WB} = 0.45$

$APL = 0$

$ADT = 2{,}800$

$K = 11\%$

$D = 55\%$

Using Equation 1:

$NPO_{EB} = 0.42$

$NPO_{WB} = 0.33$

Accordingly, the following Level 2 warning message was appropriate:

Supply of passing opportunities between Stations XXX + XX and YYY + YY may be insufficient. An LOS investigation using the HCM procedures for two-lane highways is recommended.

The following rules were not applied because no passing lanes were present: *passing lane too short*, *passing lane too long*, and *passing lane addition channels slow vehicles into left lane*.

Frequency of Decisions on Roadway Segments

The test section was reviewed for the presence of the following features to test the rule *frequency of decisions on roadway segments*:

- Intersection [present];
- Major driveway [not present];
- Railroad-highway grade crossing [not present];
- Beginning or end of a horizontal curve with radius less than 800 m [2,600 ft] [present];
- Vertical curve with available SSD less than that given in the Green Book for a design speed equal to 20 km/h [10 mph] less than the roadway operating speed [not present];
- School zone [not present];
- Narrow bridge (curb-to-curb width less than the roadway approach including paved shoulder) [not present];
- Change in posted speed limit [present];
- Lane addition [present];
- Lane drop [present];
- Lane width reduction by 0.6 m [2 ft] or more [not present]; and
- Shoulder width reduction by 1.2 m [4 ft] or more [not present].

Although several of the individual critical features were present, their locations were sufficiently separated in distance that no warnings were generated.

Preview Sight Distance

The test section was reviewed for the presence of the following features:

- School zones,
- Passing/climbing lane drops,
- Narrow bridges,
- Lane width reductions,
- Shoulder width reductions,
- Railroad-highway grade crossings, and
- Major driveways.

None of the features were present on the test section, so the rule was not applied.

APPENDIX E

RECOMMENDED CHANGES TO THE AASHTO GREEN BOOK

The AASHTO Green Book provides guidance to designers and engineers regarding the design of highways and streets. Recommendations for changes to Chapter 2, Design Controls and Criteria, Driver Performance, pages 46-57, are provided. Text proposed for insertion is underlined. No text is proposed for deletion.

DRIVER PERFORMANCE

Introduction

An appreciation of driver performance is essential to proper highway design and operation. The suitability of a design rests as much on how safely and efficiently drivers are able to use the highway as on any other criterion. When drivers use a highway designed to be compatible with their capabilities and limitations, their performance is aided. When a design is incompatible with the capabilities of drivers, the chance for driver errors increase, and crashes or inefficient operation may result.

This section provides information about driver performance useful to highway engineers in designing and operating highways. It describes drivers in terms of their performance—how they interact with the highway and its information system and why they make errors.

The material draws extensively from A User's Guide to Positive Guidance (4), which contains information on driver attributes, driving tasks, and information handling by the driver.

Where positive guidance is applied to design, competent drivers, using well-designed highways with appropriate information displays, can perform safely and efficiently. Properly designed and operated highways, in turn, provide positive guidance to drivers. In addition, Transportation Research Record 1281 entitled Human Factors and Safety Research Related to Highway Design and Operations (5), provides background information.

Older Drivers

At the start of the 20th century, approximately 4 percent of America's population was 65 years of age or older. This group, which accounted for 15 percent of the driving population in 1986, and is expected to increase to 22 percent by the year 2030.

Older drivers and pedestrians are a significant and rapidly growing segment of the highway user population with a variety of age-related diminished capabilities. As a group, they have the potential to adversely affect the highway system's safety and efficiency. There is agreement that older road users require mobility and that they should be accommodated by the design and operational characteristics of a highway to the extent practical.

Older drivers have special needs that should be considered in highway design and traffic control. For example, for every decade after age 25, drivers need twice the brightness at night to receive visual information. Hence, by age 75, some drivers may need 32 times the brightness they did at age 25.

Research findings show that enhancements to the highway system to improve its usability for older drivers and pedestrians can also improve the system for all users. Thus, designers and engineers should be aware of the capabilities and needs of older road users and consider appropriate measures to aid their performance. A Federal Highway Administration report, entitled Older Driver Highway Design Handbook: Recommendations and Guidelines (6), provides information on how geometric design elements and traffic control devices can be modified to better meet the needs and capabilities of older road users.

The Driving Task

The driving task depends on drivers receiving and using information correctly. The information received by drivers as they travel is compared with the information they already possess. Decisions are then made by drivers based on the information available to them and appropriate control actions are taken.

Driving encompasses a number of discrete and interrelated activities. When grouped by performance, the components of the driving task fall into three levels: control, guidance, and navigation. These activities are ordered on scales of complexity of task and importance for safety. Simple steering and speed control are at one end of the scale (control). Road-following and safe path maintenance in response to road and traffic conditions are at midlevel of the scale (guidance). At the other end of the scale are trip planning and route following (navigation).

The driving task may be complex and demanding, and several individual activities may need to be performed simultaneously, requiring smooth and efficient processing and integration of information. Driving often occurs at high speeds, under time pressure, in unfamiliar locations, and under adverse environmental conditions. The driving task may at other times be so simple and undemanding that a driver becomes inattentive. The key to safe, efficient driver performance in this broad range of driving situations is error-free information handling.

Driver errors result from many driver, vehicle, roadway, and traffic factors. Some driver errors occur because drivers may not always recognize what particular roadway traffic situations are require of them, because situations may lead to task overload or inattentiveness, and because deficient or inconsistent designs or information displays may cause confusion. Driver errors may also result from pressures of time, complexity of decisions, or profusion of information. Control and guidance errors by drivers may also contribute directly to crashes. In addition, navigational errors resulting in delay contribute to inefficient operations and may lead indirectly to crashes.

The Guidance Task

Of the three major components of the driving task, highway design and traffic operations have the greatest effect on guidance. An appreciation of the guidance component of the driving task is needed by the highway designer to aid driver performance.

Lane Placement and Road Following

Lane placement and road-following decisions, including steering and speed control judgments, are basic to vehicle guidance. Drivers use a feedback process to follow alignment and grade within the constraints of road and environmental conditions. Obstacle-avoidance decisions are integrated into lane placement and road-following activities. This portion of the guidance task level is continually performed both when no other traffic is present (singularly) or when it is shared with other activities (integrated).

Car Following

Car following is the process by which drivers guide their vehicles when following another vehicle. Car-following decisions are more complex than road-following decisions because they involve speed-control modifications. In car following, drivers need to constantly modify their speed to maintain safe gaps between vehicles. To proceed safely, they have to assess the speed of the lead vehicle and the speed and position of other vehicles in the traffic stream and continually detect, assess, and respond to changes.

Passing Maneuvers

The driver decision to initiate, continue, or complete a passing maneuver is even more complex than the decisions involved in lane placement or car following. Passing decisions require modifications in road- and car-following and in speed control. In passing, drivers must judge the speed and acceleration potential of their own vehicle, the speed of the lead vehicle, the speed and rate of closure of the approached vehicle, and the presence of an acceptable gap in the traffic morning period.

Other Guidance Activities

Other guidance activities include merging, lane changing, avoidance of pedestrians, and response to traffic control devices. These activities also require complex decisions, judgments, and predictions.

The Information System

Each element that provides information to drivers is part of the information system of the highway. Formal sources of information are the traffic control devices specifically designed to display information to drivers. Informal sources include such elements as roadway and roadside design features, pavement joints, tree lines, and traffic. Together, the formal and informal sources provide the information drivers need to drive safely and efficiently. Formal and informal sources of information are interrelated and must reinforce and augment each other to be most useful.

Traffic Control Devices

Traffic control devices provide guidance and navigation information that often is not otherwise available or apparent. Such devices include regulatory, warning, and guide signs, and other route guidance information. Other traffic control devices, such as markings and delineation, display additional information that augments particular roadway or environmental features. These devices help drivers perceive information that might otherwise be overlooked or difficult to recognize. Information on the appropriate use of traffic control devices is presented in the Manual on Uniform Traffic Control Devices (7).

The Roadway and its Environment

Selection of speeds and paths is dependent on drivers being able to see the road ahead. Drivers must see the road directly in front of their vehicles and far enough in advance to perceive with a high degree of accuracy the alignment, profile gradeline, and related aspects of the roadway. The view of the road also includes the environment immediately adjacent to the roadway. Such appurtenances as shoulders and roadside obstacles (including sign supports, bridge piers, abutments, guardrail, and median barriers) affect driving behavior and, therefore, should be clearly visible to the driver.

Information Handling

Drivers use many of their senses to gather information. Most information is received visually by drivers from their view of the roadway alignment, markings, and signs. However, drivers also detect changes in vehicle handling through instinct. They do so, for example, by feeling road surface texture through vibrations in the steering wheel and hearing emergency vehicle sirens. Throughout the driving task, drivers perform several functions almost simultaneously. They look at information sources, make numerous decisions, and perform necessary control actions.

Sources of information (some needed, others not) compete for their attention. Needed information should be in the driver's field of view, available when and where needed, available in a usable form, and capable of capturing the driver's attention.

Because drivers can only attend to one visual information source at a time, they integrate the various information inputs and maintain an awareness of the changing environment through an attention-sharing process. Drivers sample visual information obtained in short-duration glances, shifting their attention from one source to another. They make some decisions immediately, and delay others, through reliance on judgment, estimation, and prediction to fill in gaps in available information.

Reaction Time

Information takes time to process. Drivers' reaction times increase as a function of decision complexity and the amount of information to be processed. Furthermore, the longer the reaction time, the greater the chance for error. Johannson and Rumar (8) measured brake reaction time for expected and unexpected events. Their results show that when an event is expected, reaction time averages about 0.6 s, with a few drivers taking as long as 2 s. With unexpected events, reaction times increased by 35 percent. Thus, for a simple, unexpected decision and action, some drivers may take as long as 2.7 s to respond. A complex decision with several alternatives may take several seconds longer than a simple decision. Exhibit 2-26 shows this relationship for median-case drivers, whereas Exhibit 2-27 shows this relationship for 85th-percentile drivers. The figures quantify the amount of information to be processed in bits. Long processing times decrease the time available to attend to other tasks and increase the chance for error.

Highway designs should take reaction times into account. It should be recognized that drivers vary in their responses to particular events and take longer to respond when decisions are complex or events are unexpected. Clear sight lines and adequate decision sight distance provide a margin for error.

Primacy

Primacy relates the relative importance to safety of competing information. Control and guidance information is important because the related errors may contribute directly to crashes. Navigation information has a lower primacy because errors may lead to inefficient traffic flow, but are less likely to lead to crashes. Accordingly, the design should focus the drivers' attention on the safety-critical design elements and high-priority information sources. This goal may be achieved by providing clear sight lines and good visual quality.

Expectancy

Driver expectancies are formed by the experience and training of drivers. Situations that generally occur in the same way, and successful responses to these situations, are incorporated into each driver's store of knowledge. Expectancy relates to the likelihood that a driver will respond to common situations in predictable ways that the driver has found successful in the past. Expectancy affects how drivers perceive and handle information and modify the speed and nature of their responses.

Reinforced expectancies help drivers respond rapidly and correctly. Unusual, unique, or uncommon situations that violate driver expectancies may cause longer response times, inappropriate responses, or errors.

Most highway design features are sufficiently similar to create driver expectancies related to common geometric, operational, and route characteristics. For example, because most freeway interchanges have exits on the right side of the road, drivers generally expect to exit from the right. This aids performance by enabling rapid and correct responses when exits on the right are to be negotiated. There are, however, instances where expectancies are violated. For example, if an exit ramp is on the left, then the right-exit expectancy is incorrect, and response times may be lengthened or errors committed.

One of the most important ways to aid driver performance is to develop designs in accordance with prevalent driver expectancies. Unusual design features should be avoided, and design elements should be applied consistently throughout a highway segment. Care should also be taken to maintain consistency from one segment to another. When drivers obtain the information they expect from the highway and its traffic control devices, their performance tends to be error free. Where they do not get what they expect, or get what they do not expect, errors may result.

Design Consistency

Design consistency is the conformance of a highway's geometric and operational features with driver expectancy. Measures that have been used to assess design consistency are changes in predicted 85th percentile speed, driver information handling, driver workload, changes in predicted roadway safety, and lane positioning.

Consistency with respect to these measures can help to ensure that roadway designs are developed that minimize the potential for driver error.

Driver Error

A common characteristic of many high-crash locations is that they place large or unusual demands on the information-processing capabilities of drivers. Inefficient operation and crashes usually occur where the driver's chances for information-handling errors are high. At locations where information-processing demands on the driver are high, the possibility of error and inappropriate driver performance increases.

Errors Due to Driver Deficiencies

Many driving errors are caused by deficiencies in a driver's capabilities or temporary states, which, in conjunction with inappropriate designs or difficult traffic situations, may produce a failure in judgment. For example, insufficient experience and training may contribute to a driver's inability to recover from a skid. Similarly, inappropriate risk taking may lead to errors in gap acceptance while passing (9). In addition, poor glare recovery may cause older drivers to miss information at night (10).

Adverse psychophysiological states also lead to driver failures. These include decreased performance caused by alcohol and drugs, for which a link to crashes has been clearly established. The effects of fatigue, caused by sleep deprivation from extended periods of driving without rest or prolonged exposure to monotonous environments, or both, also contribute to crashes (11).

It is not generally possible for a design or an operational procedure to reduce errors caused by innate driver deficiencies. However, designs should be as forgiving as practical to lessen the consequences of such failures. Errors committed by competent drivers can be reduced by proper design and operation. Most individuals possess the attributes and skills to drive properly and are neither drunk, drugged, nor fatigued at the start of their trips. When drivers overextend themselves, fail to take proper rest breaks, or drive for prolonged periods, they ultimately reach a less-than-competent state. Fatigued drivers represent a sizable portion of the long-trip driving population and should therefore be considered in freeway design.

Although opinions among experts are not unanimous, there is general agreement that advancing age has a deleterious effect on an individual's perceptual, mental, and motor skills. These skills are critical factors in vehicular operation. Therefore, it is important for the road designer to be aware of the needs of the older driver, and where appropriate, to consider these needs in the roadway design.

Some of the more important information and observations from recent research studies concerning older drivers is summarized below:

1. **Characteristics of the Older Driver**. In comparison to younger drivers, older drivers often exhibit the following operational deficiencies:

   - slower information processing,
   - slower reaction times,
   - slower decision making,
   - visual deterioration,
   - hearing deterioration,
   - decline in ability to judge time, speed, and distance,
   - limited depth perception,
   - limited physical mobility, and
   - side effects from prescription drugs.

2. **Crash Frequency**. Older drivers are involved in a disproportionate number of crashes where there is a higher-than-average demand imposed on driving skills. The driving maneuvers that most often precipitate higher crash frequencies among older drivers include:

   - making left turns across traffic,
   - merging with high-speed traffic,
   - changing lanes on congested streets in order to make a turn,
   - crossing a high-volume intersection,
   - stopping quickly for queued traffic, and
   - parking.

3. **Countermeasures**. The following countermeasures may help to alleviate the potential problems of the older driver:

   - assess all guidelines to consider the practicality of designing for the 95th- or 99th-percentile driver, as appropriate, to represent the performance abilities of an older driver,
   - improve sight distance by modifying designs and removing obstructions, particularly at intersections and interchanges,
   - assess sight triangles for adequacy of sight distance,
   - provide decision sight distances,
   - simplify and redesign intersections and interchanges that require multiple information, reception and processing,
   - consider alternate designs to reduce conflicts,
   - increase use of protected left-turn signal phases,
   - increase vehicular clearance times at signalized intersections,
   - provide increased walk times for pedestrians,
   - provide wider and brighter pavement markings,
   - provide larger and brighter signs,
   - reduce sign clutter,
   - provide more redundant information such as advance guide signs for street name, indications of upcoming turn lanes, and right-angle arrows ahead of an intersection where a route turns or where directional information is needed,
   - enforce speed limits, and
   - increase driver education.

In roadway design, perhaps the most practical measure related to better accommodate older drivers is an increase in sight distance, which may be accomplished through increased use of decision sight distance. The gradual aging of the driver population suggests that increased use of decision sight distance may help to reduce future crash frequencies for older drivers. Where provision of decision sight distance is impractical, increased use of advance warning or guide signs may be appropriate.

Errors Due to Situation Demands

Drivers often commit errors when they have to perform several highly complex tasks simultaneously under extreme time pressure (12). Errors of this type usually occur at urban locations with closely spaced decision points, intensive land use, complex design features, and heavy traffic. Information-processing demands beyond the drivers' capabilities may cause information overload or confuse drivers, resulting in an inadequate understanding of the driving situation.

Other locations present the opposite situations and are associated with different types of driver errors. Typically these are rural locations where there may be widely spaced decision points, sparse land use, smooth alignment, and light traffic. Information demands are thus minimal, and rather than being overloaded with information, the lack of information and decision-making demands may result in inattentiveness by drivers. Driving errors may be caused by a state of decreased vigilance in which drivers fail to detect, recognize, or respond to new, infrequently encountered, or unexpected design elements or information sources.

Speed and Design

Speed reduces the visual field, restricts peripheral vision, and limits the time available for drivers to receive and process information. Highways built to accommodate high speeds help compensate for these limitations by simplifying control and guidance activities, by aiding drivers with appropriate information, by placing this information within the cone of clear vision, by eliminating much of the need for peripheral vision, and by simplifying the decisions required and spacing them farther apart to decrease information-processing demands.

Current freeway designs have nearly reached the goal of allowing drivers to operate at high speeds in comfort and safety. Control of access to the traveled way reduces the potential for conflicts by giving drivers a clear path. Clear roadsides have been provided by eliminating obstructions or designing them to be more forgiving. The modern freeway provides an alignment and profile that, together with other factors, encourages high operating speeds.

Although improved design has produced significant benefits, it has also created potential problems. For example, driving at night at high speeds may lead to reduced forward vision because of the inability of headlights to illuminate objects in the driver's path in sufficient time for some drivers to respond (13). In addition, the severity of crashes is generally greater with increased speed.

Finally, the very fact that freeways succeed in providing safe, efficient transportation can lead to difficulties. The Institute of Traffic Engineers (14) indicated that "Freeways encourage drivers to extend the customary length and duration of their trips. This results in driver fatigue and slower reaction as well as a reduction in attention and vigilance."

Thus, extended periods of high-speed driving on highways with low demand for information processing may not always be conducive to proper information handling by drivers and may therefore lead to driver fatigue. Highway design should take these possible adverse effects into account and seek to lessen their consequences. For example, long sections of flat, tangent roadway should be avoided and flat, curving alignment that follows the natural contours of the terrain should be used whenever practical. Rest areas spaced at intervals of approximately one hour or less of driving time have also proved beneficial.

Design Assessment

The preceding sections of this chapter have described the way drivers use information provided by the highway and its appurtenances. This discussion has shown the interdependence between design and information display. Both should be assessed in the design of highway projects.

Because drivers "read" the road and the adjacent environment and make decisions based on what they see (even if traffic control devices making up the formal information system indicate inconsistencies with the driver's view), a highway segment that is inappropriately designed may not operate safely and efficiently. Conversely, an adequately designed highway may not operate properly without the appropriate complement of traffic control devices.

Designers should consider how the highway will fit into the existing landscape, how the highway should be signed, and the extent to which the information system will complement and augment the proposed design. The view of the road is very important, especially to the unfamiliar driver. Therefore, consideration should be given to the visual qualities of the road. This can be accomplished through the use of 3-D computer visualization programs.

Locations with potential for information overload should be identified and corrected. The adequacy of the sight lines and sight distances should be assessed, and it should be determined whether unusual vehicle maneuvers are required and whether likely driver expectancies may be violated.

<u>Roadway designs can be assessed for potential inconsistencies with regard to 85th percentile speed. FHWA has developed a tool that can be used to predict where large changes in 85th percentile speed may occur on rural two-lane roadways: the Interactive Highway Safety Design Model (IHSDM). This model allows the user to detect locations where the changes in 85th percentile speed may lead to safety problems on the completed roadway.</u>

<u>Designers can also use design consistency rules for rural two-lane roadways developed in NCHRP 15-17 to determine where design inconsistencies related to changes in predicted safety, speed, and lane positioning may be found. Rules for</u>

detecting design inconsistencies related to cross section, horizontal and vertical alignment, driveways, railroad grade crossings, sight distance, narrow bridges, and decision frequency were developed in the study.

Potential driver problems can be anticipated before a facility is built by using information about the driving tasks and possible driver errors to assess the design. When trade-offs are appropriate, they should be made with the drivers' capabilities in mind to ensure that the resultant design is compatible with those capabilities. Properly designed highways that provide positive guidance to drivers can operate at a high level of safety and efficiency; therefore, designers should seek to incorporate these principles in highway design.

Abbreviations used without definitions in TRB publications:

AASHO	American Association of State Highway Officials
AASHTO	American Association of State Highway and Transportation Officials
APTA	American Public Transportation Association
ASCE	American Society of Civil Engineers
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
ATA	American Trucking Associations
CTAA	Community Transportation Association of America
CTBSSP	Commercial Truck and Bus Safety Synthesis Program
FAA	Federal Aviation Administration
FHWA	Federal Highway Administration
FMCSA	Federal Motor Carrier Safety Administration
FRA	Federal Railroad Administration
FTA	Federal Transit Administration
IEEE	Institute of Electrical and Electronics Engineers
ITE	Institute of Transportation Engineers
NCHRP	National Cooperative Highway Research Program
NCTRP	National Cooperative Transit Research and Development Program
NHTSA	National Highway Traffic Safety Administration
NTSB	National Transportation Safety Board
SAE	Society of Automotive Engineers
TCRP	Transit Cooperative Research Program
TRB	Transportation Research Board
U.S.DOT	United States Department of Transportation